PHYSICAL
SCI. LIB.

QE
89
A1
C32
no.63

Digitized by the Internet Archive
in 2012 with funding from
University of California, Davis Libraries

http://archive.org/details/specialpublicati63cali

PHYSICAL SCI. LIB.
E89
A1
32
S
63

STATUS OF VOLCANIC PREDICTION AND EMERGENCY RESPONSE CAPABILITIES VOLCANIC HAZARD ZONES OF CALIFORNIA

Mt. Lassen in eruption 1915

SPECIAL PUBLICATION 63

PROCEEDINGS OF A WORKSHOP
ON VOLCANIC HAZARDS IN CALIFORNIA
DECEMBER 3—4, 1981, SACRAMENTO

UNIVERSITY OF CALIFORNIA
DAVIS
APR 0 1983
CALIF. DEPOS.
GOVT DOCS. - LIBRARY

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY

STATE OF CALIFORNIA
EDMUND G. BROWN JR.
GOVERNOR

THE RESOURCES AGENCY
HUEY D. JOHNSON
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
JAN DENTON
DIRECTOR

DIVISION OF MINES AND GEOLOGY
JAMES F. DAVIS
STATE GEOLOGIST

SPECIAL PUBLICATION 63

STATUS OF VOLCANIC PREDICTION AND EMERGENCY RESPONSE CAPABILITIES IN VOLCANIC HAZARD ZONES OF CALIFORNIA

Edited by
Roger C. Martin
and
James F. Davis

1982

Proceedings of a Workshop
on Volcanic Hazards in California,
December 3-4, 1981,
Sacramento, California

Sponsored by
the California Department of Conservation's Division of Mines
and Geology and the California Office of Emergency Services

California Department of Conservation
Division of Mines and Geology
1416 Ninth Street, Room 1341
Sacramento, California 95814

PREFACE

Until recently, most Californians were oblivious to volcanoes. Many had learned at an early age that the only "active" volcano (Lassen Peak) in the conterminous 48 States had last erupted in California during the years 1914-1917. But most perceived volcanoes simply as interesting cone-shaped mountains that erupt only in distant romantic places such as Hawaii, Central America, Indonesia, and Iceland. The disaster or hazard potential of volcanoes, portrayed by books and popular movies, was also associated with distant romantic places: Pompeii, 79 AD; Krakatoa (west of Java), 1883; and St. Pierre on Martinique, 1902.

In a sense, our awareness of volcanic activity as a hazard in California was similar to our concern for earthquake hazards in 1933, before the destructive Long Beach earthquake. Everyone knew that earthquake destruction was possible, but government and industry were not sufficiently concerned to prepare for it.

The cataclysmic eruption of Mount St. Helens, in 1980, changed our perceptions abruptly. The resulting losses of life and property damage and the spectacular devastation of a large region of forest and lakes impacted the economic and social outlook of Washington State and produced nationwide reaction and worldwide attention.

Recently, geologists working in California have begun to investigate the volcanic hazard potential of some volcanic areas of California. Lassen Peak has been dethroned from its position as the only active volcano in the conterminous USA, and some now regard it as not even the most likely candidate in California to erupt next. Geologic attention has been turning to the Long Valley caldera, Mono Lake, and Mount Shasta areas, which, while not as recently active as Lassen, nevertheless show evidence of a very active recent history, or of current earth movements of volcanic nature that warrant concern.

Coping with this newly recognized natural hazard is not an entirely unusual or alien problem for the State. A close similarity of the effects of volcanic and seismic hazards is obvious, and the California Division of Mines and Geology (DMG) and the California Office of Emergency Services (OES) have been among the world leaders in governmental groups attempting to safeguard the public through scientific studies and preparation training.

The Mount St. Helens experience brought home a realization of the massive information needs for California to adequately cope with a similar volcanic disaster. A DMG-OES task force, headed by the State Geologist, recognized the following information needs, and plans were made to attract the best qualified experts available to address these questions:

- What portions of the state have the greatest probability of volcanic eruption? What information is required to establish priorities for the study of these potentially active volcanic areas?

- What types of monitoring or observation should be employed in the most vulnerable portions of the state to insure public safety? Who should conduct the monitoring?

- What types of volcanic eruptions are most likely in the active volcanic terrains?

- Can we expect to employ techniques of volcanic eruption prediction established at Mount St. Helens in our emergency response planning efforts in California?

- What types of earth science research are needed to improve our capability of dealing with volcanic eruptions in California?

- What types of scientific information exchange will serve to expedite research and provide information for emergency planning?

- What scope of planning will best assure the proper management of a volcanic eruption emergency in California?

- What differences in emergency plans are necessary in the development of response activities to deal with the predictions of an volcanic eruption as compared with dealing with the eruption itself?

- What responsibilities and roles are appropriate for federal, State, and local officials in emergency response to a volcanic eruption?

- What are the federal, State, and local responsibilities and roles in emergency response to a prediction of a volcanic eruption?

- Are federal "hazard notice, watch and warning" terminologies appropriate to volcanic hazards in California? How has the volcanic hazards watch status of the Mammoth Lakes area served public safety in the region?

- What types of emergency communication between parties will be required during the response to a prediction? to an eruption?

- What variations in emergency response plans are required by the possible variations in the types of eruptions which may be expected in specific regions of volcanic activity?

- Are there any social science research results which should be but are not being applied to emergency response planning?

- What type of social behavioral research can enhance our emergency responses to volcanic activity in California?

- What insights from Mount St. Helens can be applied to managing public information and emergency response in the general volcanic circumstances in California?

- What type of information clearinghouse is needed between the emergency response and the scientific communities in an emergency situation?

- What types of conferences or workshops can extend our understanding of what still needs to be done in emergency planning and application of scientific insights to public safety?

This workshop was convened December 3 and 4, 1981, in Sacramento. Two hundred individuals representing a wide range of backgrounds, fields of interest, and areas of professional expertise participated in the workshop. We believe that the information exchange and interaction that occurred when these individuals came together generated significant insights pertinent to the above questions.

Perhaps it was the recent Mount St. Helens experience that kindled the lively awareness, interest, and concern of the workshop participants. Certainly during these two days an appreciation for the opportunity to communicate with widely differing professional groups was evident. Government leaders, planners, emergency response officials, and social scientists, as well as volcanologists, expressed their common need for preparation and group cooperation in dealing with a volcanic emergency.

On the first day, volcanic scientists ably summarized their knowledge of potential volcanic hazards zones in California, explained their recent accomplishments in studies to predict volcanic activity, and pin-pointed their deficiencies in this relatively young research field. On the second day, public leaders and human-response personnel related their problems in dealing with the public and the media, and emphasized their need for clear, consistent scientific advice during a volcanic emergency, especially the need for precise (deterministic) predictions of volcanic activity, to prevent loss of lives.

Perhaps the most pertinent of all expressions to arise in this workshop was that, for the low-probability, high-consequence hazards such as future volcanism in California, now is the time for scientists and public leaders to communicate on this issue so that modern planning and disaster preparations can be performed prior to a coming eruption, not during and afterward, as was essentially the case at Mount St. Helens.

Roger C. Martin
Senior Scientist, Volcanology

James F. Davis
State Geologist

CONTENTS

Page

PREFACE iii

PRINCIPAL CONTRIBUTORS xi

PART I: VOLCANIC HAZARDS IN CALIFORNIA AND STATE-OF-THE-ART IN PREDICTION OF VOLCANIC ACTIVITY

WELCOME

Jan Denton 3

INTRODUCTORY REMARKS

James F. Davis 5

POTENTIALLY ACTIVE VOLCANIC ZONES IN CALIFORNIA

Charles W. Chesterman 9

OTHER POTENTIAL ERUPTION CENTERS IN CALIFORNIA: LONG VALLEY-MONO LAKE, COSO, AND CLEAR LAKE VOLCANO FIELDS

Roy A. Bailey 17

CHRONOLOGY OF ERUPTIONS IN CALIFORNIA DURING THE LAST 2,000 YEARS

Richard T. Kilbourne 29

VOLCANIC HAZARD POTENTIAL IN THE CALIFORNIA CASCADES

Robert L. Christiansen 41

DESCRIPTION OF U.S. GEOLOGICAL SURVEY STUDIES OF POTENTIAL HAZARDS FROM FUTURE ERUPTIONS IN CALIFORNIA

C. Dan Miller 61

IMPACTS OF THE MOUNT ST. HELENS ERUPTION ON INDUSTRY

Clive F. Kienle 63

REALISTIC VOLCANIC HAZARDS ASSESSMENT AND THE IMPORTANCE OF FREQUENCY/EXPLOSIVITY RELATIONS

Alexander R. McBirney 71

THE MOUNT ST. HELENS ERUPTIONS: SEISMIC MONITORING FOR ERUPTION PREDICTION

Steve Malone 79

THE CYCLICAL NATURE OF EXPLOSIVE VOLCANISM: A PETROLOGICAL APPROACH TO VOLCANO FORECASTING

William C. Melson 99

ADDITIONAL GEOPHYSICAL TECHNIQUES FOR MONITORING VOLCANOES: GEODETIC, GRAVITY, THERMAL, ELECTRICAL, MAGNETIC, AND RADIOACTIVITY

Robert W. Decker 119

THERMAL INFRARED IMAGERY OF THE CASCADE RANGE VOLCANICS

I. William Ginsberg 131

PANEL DISCUSSION I: FORECASTING ERUPTIVE ACTIVITY IN CALIFORNIA - APPROPRIATE MONITORING METHODS FOR THE DIVERSE VOLCANIC ENVIRONMENTS 137

PART II: HUMAN RESPONSE TO VOLCANIC DISASTERS: HAZARDS PLANNING AND EMERGENCY OPERATIONS

SPECIAL HUMAN BEHAVIORAL RESPONSE ASSOCIATED WITH VOLCANIC HAZARD CONDITIONS

Gilbert F. White 147

EMERGENCY PLANNING FOR RARE EVENTS: SOME BEHAVIORAL SCIENCE LESSONS FOR VOLCANO HAZARD MANAGEMENT

John H. Sorensen 153

EMERGENCY PLANNING IMPLICATIONS OF LOCAL GOVERNMENTS' ADAPTIVE RESPONSE TO MOUNT ST. HELENS

Jack D. Kartez 169

U.S. GEOLOGICAL SURVEY ROLE AT MOUNT ST. HELENS BEFORE AND DURING EARLY 1980-GEOLOGIC STUDIES AND COORDINATION WITH PUBLIC AGENCIES

Donal R. Mullineaux 187

OPERATIONS OF THE U.S. GEOLOGICAL SURVEY AT MOUNT ST. HELENS

Donald W. Peterson 193

ROLE OF THE U.S. FOREST SERVICE AT MOUNT ST. HELENS

Jerry J. Brown 205

LOCAL GOVERNMENT'S EXPERIENCE AT MOUNT ST. HELENS

Les Nelson 213

IMPACT OF THE ERUPTIONS ON CITY GOVERNMENT

Betty L. Edmondson 219

PANEL DISCUSSION II: EMERGENCY PROBLEMS FOLLOWING THE ERUPTIONS 223

VOLCANO EMERGENCY INVOLVEMENT AT THE FEDERAL LEVEL

Robert C. Stevens 227

ROLE OF THE CALIFORNIA OFFICE OF EMERGENCY SERVICES IN NATURAL DISASTERS

Alex R. Cunningham 243

THE CALIFORNIA STATE GOVERNMENT'S ROLE IN NATURAL HAZARD EMERGENCIES: A LEGISLATIVE PERSPECTIVE

Joe Lang 251

PANEL DISCUSSION III: APPLYING THE STATE OF SCIENTIFIC KNOWLEDGE, AND RECENT VOLCANIC HAZARDS EXPERIENCE TO CALIFORNIA EMERGENCY RESPONSE STRATEGIES 255

WORKSHOP SUMMATION AND CONCLUDING REMARKS 263

LIST OF PARTICIPANTS AND ATTENDEES 265

GLOSSARY 269

PRINCIPAL CONTRIBUTORS

Dr. Roy A. Bailey is Coordinator of the U.S. Geological Survey's Volcano Hazards Program, and is currently participating in a volcano hazards study of the Mono-Inyo Craters in California. As a member of the USGS since 1950, he has spent most of his career mapping and investigating volcanic rocks and processes, mainly in the Jemez Mountains and Long Valley volcanic complexes. He visited or worked on volcanoes in New Zealand, Japan, Alaska, Hawaii and the West Indies.

Jerry J. Brown is Fire Management Staff Officer and Director of the Cascades Volcanoes Emergency Coordinating Center. He has served in a fire staff officer capacity for the U.S. Forest Service since 1969, and accepted an assignment with the United Nations Food and Agriculture Organization in Nigeria as a Wildland Fire Protection Consultant until reassignment to his present location at the Gifford Pinchot National Forest.

Charles W. Chesterman joined the California Division of Mines and Geology in 1947 and worked as a geologist in various capacities there until his retirement as Senior Scientist in 1978. Since 1955, he has been Honorary Curator of Mineralogy at the California Academy of Sciences, and now lectures in mineralogy for the Docents Council of the California Academy of Sciences. He has authored more than 60 papers on California minerals, volcanoes and general geology.

Dr. Robert L. Christiansen has been with the U.S. Geological Survey since 1961. His research has concentrated on both active and ancient volcanoes, and focused on problems associated with explosive volcanism or with voluminous silicic volcanic systems. He organized and coordinated the Geological Survey's program of monitoring and scientific analysis during the first five months of Mount St. Helens' eruptions in 1980.

Alex R. Cunningham is the Director of Emergency Services for the State of California and is responsible for ensuring that State government is prepared to provide support wherever requested in the State in the event of a natural disaster or war emergency. As such, he is also the Chief of Emergency Planning for the State, providing assistance to local governments. He is past president of the National Emergency Management Association (NEMA) and is a Lt. Colonel in the California National Guard.

Dr. James F. Davis has been the State Geologist and Chief of the California Division of Mines and Geology since 1978. He has broad interests in the applications of earth science to public policy which have included nuclear power plant siting, dam design requirements, slope stability, volcanism and seismicity. Dr. Davis formerly served as State Geologist and Chief Scientist of the New York State Geological survey. He presently serves as Chairman on the Governor's Emergency Task Force on Earthquake Preparedness, Threat Assessment Committee, and is Chairman of the California Earthquake Prediction Evaluations Counsel.

Jan Denton was appointed by Governor Brown in March 1981 as the Director of the California Department of Conservation. As Director, she is responsible for overseeing the Divisions of Mines and Geology, Oil and Gas, the Land Resources Protection Unit, the State Mining and Geology Board, and the Geothermal Resources Board; and to direct them towards a wide and safe use of the earth's resources. Ms. Denton was formerly Assistant Secretary for Legislation within the Resources Agency, and represented the Agency before the California State Legislature for two years.

Dr. Robert W. Decker is Scientist-in-Charge of the Hawaiian Volcano Observatory with the U.S. Geological Survey. His field of studies include volcanism and tectonics in Indonesia, Iceland, Central America, Hawaii and the western United States. He is past president of the International Association of Volcanology and Chemistry of the Earth's Interior, and has taught volcanology for 25 years at Dartmouth College.

Betty Edmondson, former Mayor of Yakima, Washington, is an active member of the community in various groups such as the Yakima City Council, American Red Cross Blood Bank Program, and an appointee to such commissions as the National League of Cities, United States Conference of Mayors, and the Governor's Advisory Committee on Voluntary Service.

Dr. I. William Ginsberg is Manager of the Multispectral Remote Sensing Department at EG&G, Inc. The department is one part of EG&G's Aerial Measurements Operations/Remote Sensing Laboratory and is located in Las Vegas, Nevada. Dr. Ginsberg is responsible for the management and technical direction of all non-photographic remote sensing data acquisition and computer analysis. This includes multispectral infrared scanners and imagers, ground truth instrumentation, a dedicated image processing system for data analysis, and microdensitometer for digitizing photography.

Dr. Jack D. Kartez is an Assistant Professor of Environmental Science and Regional Planning at Washington State University. Specializing in developments of new techniques for policy planning and evaluation, he has sought to apply innovative methods of analysis to policy issues surrounding growth management, farmland preservation, regulatory reform and disaster preparedness planning.

Dr. Clive F. (Rick) Kienle is Volcanic Stratigrapher and Structural Geologist with Foundation Sciences, Inc. He is responsible for geologic and geophysical investigations related to siting studies, geotechnical design of underground and surface structures, seismic studies, and other engineering geologic projects. He directed an extensive study of Mount St. Helens geologic hazards and investigated ash fall hazards for Portland General Electric's Trojan nuclear power plant.

Dr. Richard T. Kilbourne works as a Geologist with the San Francisco District Office of the California Division of Mines and Geology, specializing in geologic hazards. He has applied his age-dating and Quaternary geology skills to the assessment of geologic hazards including faults, landslides, and volcanoes.

Joe Lang is a consultant for the Commission on Government Organization of the California State Assembly in Sacramento, California. He joined the Assembly staff in 1975, and was appointed to his current position as Senior consultant to the Assembly Governmental Organization Committee in December 1976. His field of expertise includes general services, veterans affairs, emergency services and alcoholic beverage laws. Among his various publications is Preparing for Disasters: An Evaluation of California's Emergency Preparedness.

Dr. Stephen D. Malone is Senior Research Associate in the Geophysics Program at the University of Washington and is a prominent leader in the field of geophysical monitoring of active volcanoes. He is actively working with the U.S. Geological Survey as Principal Investigator in seismic investigations of Mount St. Helens.

Robert A. Mathews serves as Senior Lecturer in the Department of Geology at the University of Californis, Davis. Following the 1980 eruption of Mount St. Helens, he became involved with analyzing and evaluating the U.S. Geological Survey's Hazard and Warning Program that was developed to deal with such disasters. In 1980, he was appointed to the California State Mining and Geology Board, which he serves in addition to his teaching activities.

Dr. Alexander R. McBirney is Professor of Geology and Director of the Center for Volcanology at the University of Oregon. Dr. McBirney first became interested in volcanoes while living in Central America in the early 1950's and has carried out field studies in all of the Central American countries, as well as the Galapagos Islands, the Oregon Cascades, and other parts of the world. His main interest has been in the physical processes of volcanic activity, particularly the behavior of magmas before and during eruptions.

Dr. William G. Melson is Curator-in-Charge in the Division of Petrology and Volcanology with the Smithsonian Institution. During the Mount St. Helens eruptions of 1980, he applied the study of fluid inclusions in crystals to predictions of further volcanic activity based upon trends of magmatic volatile content. He has served as co-chief scientist on two Glomar Challenger drilling projects investigating volcanic activity of the mid-ocean ridge systems.

Dr. C. Dan Miller is the USGS Research Scientist, specializing in volcanic hazards analysis. In 1980, he was the volcanic hazards coordinator during 1980 eruptions of Mount St. Helens. Dr. Miller's studies include detailed studies of the stratigraphy of Holocene eruptive deposits around volcanoes in the western U.S., including such volcanoes as Mt. Shasta, the Mono-Inyo Craters, Mount St. Helens, and other volcanoes such as Cotopaxi in Ecuador, and volcanoes on Java, Indonesia.

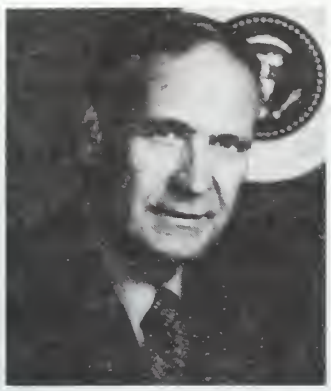
Dr. Donal Mullineaux of the U.S. Geological Survey is a recognized leader in the field of volcanic hazards assessment following studies of Mount Rainier, Lassen Peak, Island of Hawaii, Cotopaxi Volcano in Ecuador, and Mount St. Helens. He co-authored a study of the volcanic hazards of Mount St. Helens published two years before the 1980 eruption. During the eruptions, he served as Scientist-in-Charge, dealing extensively with the public and news media at the Survey's volcano observatory in Vancouver, Washington.

Leslie (Les) S. Nelson is Sheriff of Cowlitz County in Kelso, Washington. As Sheriff, Mr. Nelson took part in the Mount St. Helens volcanic hazard response activity. His role placed him in the midst of the difficulties concerning the extent of government responsibilities in relation to the immediate community. Because of his heavy involvement during the most active portions of eruptive activity, Sheriff Nelson was appointed Chairman of the Mount St. Helens Life and Property Task Force.

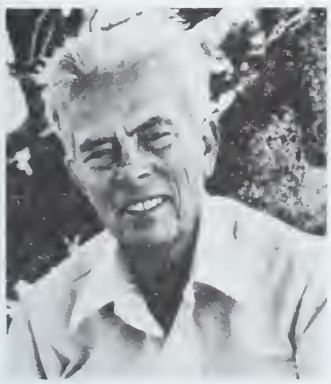
Dr. Donald W. Peterson is Scientist-in-Charge at the Mount St. Helens project where he directs the USGS Monitoring and research program, and planning of monitoring programs for other Cascade volcanoes. From 1970 to 1975, he directed the USGS monitoring and research program on Hawaii's active volcanoes as Scientist-in-Charge at Hawaiian Volcano Observatory.

Dr. Clement (Clem) F. Shearer is the Assistant Chief of the Earth Sciences Assistance Office in the U.S. Geological Survey as well as that agency's Deputy Hazards Information Coordinator. His duties include management of an interdisciplinary program for the application of earth science research and information to resource planning and other non-technical decision-making processes, and operation of the USGS Hazard Warning and Preparedness program.

Dr. John H. Sorensen, Research Associate for the Resource Analysis Group, Energy Division of Oak Ridge National Laboratory, is currently researching the assessment of the manner in which societies respond to natural and man-made hazards, with emphasis on the social consequences and associated implications for public policy.



Robert C. Stevens in the former Regional Director for the Federal Emergency Management Agency (FEMA) in San Francisco. Prior to his retirement in January 1981, he was the Federal Coordinating Officer at more than sixty major disasters, including Mount St. Helens. As Regional Director, he was responsible for the administration of all Federal Emergency Management activities in Region IX, including United States jurisdictions in the Pacific, California, Arizona, Nevada and Hawaii.



Dr. Gilbert F. White is the Director of the Natural Hazards Research and Applications Information Center at the University of Colorado in Boulder, Colorado. As a geographer, Dr. White has worked on the problems of water management and of human adjustment to natural hazards, including an assessment of research on natural hazards, and a review of international experience in dealing with floods, hurricanes, drought, earthquakes, landslides, and other natural disasters.

OTHER CONTRIBUTORS

Workshop Content and Design
Dr. Roger C. Martin, Senior Scientist, Volcanology, California Division of Mines and Geology.
Dr. James F. Davis, State Geologist, California Division of Mines and Geology.

Workshop Administration and Logistics
Barbara Zaro, Program Assistant, University Extension, University of California, Davis.

Workshop Administration Consultant
Mike McCoy, Continuing Education Specialist and Manager "Science and the Environment"
University of California Extension, Davis, California.

PART I

VOLCANIC HAZARDS IN CALIFORNIA AND STATE-OF-THE-ART IN PREDICTION OF VOLCANIC ACTIVITY

WELCOME

Jan Denton, Director
Department of Conservation
The Resources Agency
State of California

Good morning, I would like to welcome all of you here today to this Workshop on the Status of Volcanic Prediction and Emergency Response Capabilities in Volcanic Hazard Zones of California. This workshop is being sponsored by the California Department of Conservation, Division of Mines and Geology, in association with the California Office of Emergency Services.

I am very pleased to see the large attendance at this conference today; I believe it will be a very stimulating and exciting one.

This event was planned in order to learn more about the recent volcanic eruptions at Mount St. Helens and how this information might apply to California. It is not commonly known that California has at least four major active volcanic regions, with approximately 20 active volcanoes. So it is not too unrealistic to believe that what happened in the State of Washington could happen in California.

It is very presumptuous of us to forget that the earth is a dynamic environment. Occasionally, we are reminded by events such as Mount St. Helens that the earth is still very much alive. We must maintain a healthy respect for the incredible forces which shape and reshape our planet. Part of this respect includes our ability to be prepared to cope with natural occurrences which can become disasters. The state-of-the-art in predicting volcanic eruptions, as well as emergency response capabilities in the event of a volcanic eruption, are of vital importance to California.

We have an impressive array of experts, both as speakers and in the audience, assembled here for this two-day workshop. I hope that our mutual efforts will provide us with an evaluation of the volcanic conditions that exist in California; help us to analyze and relate the Mount St. Helens experience to California; and assist us in examining our state's emergency preparedness to deal with the unusual problems that can result from volcanic eruptions.

It is the goal of the Department of Conservation and our Division of Mines and Geology to serve in a critical advisory capacity to the Governor, the Office of Emergency Services, and other government agencies. We wish to encourage the combination of scientific expertise and emergency preparedness as an ongoing and critical part of the activities of government in California.

Thank you for attending this workshop and helping to make it a success.

INTRODUCTORY REMARKS

Dr. James F. Davis, State Geologist
California Department of Conservation
Division of Mines and Geology

The idea for a Volcanic Hazards Conference such as this came to mind in 1980 after the occurrence of two apparently coupled geologic events: the May Mount St. Helens eruptions, and some very unusual earthquake activity in the Mammoth Lakes area.* Four of the earthquakes were of magnitude 6 or greater. The first occurred only a week after the climactic May 18 eruption, and coincided with the explosive May 25 eruption of Mount St. Helens and brought the reality of the volcanic eruptions closer to home for most California earth scientists. We are living in an interesting time, for we now have a reasonably comprehensive model which can relate spacially volcanism and other geodynamic processes such as these along the western margin of the continent and in other parts of the world. These spacial relations are basically functional or mechanical in nature.

On the other hand, when we attempt to explain the time relations of such events, we find the state of our knowledge is more empirical and anecdotal than statistical and rigorous. One of the challenges we have, both in working with earthquakes and with volcanism, is to develop a means of anticipating what will happen on the broader time-scale and then to refine our forecasting ability to a progressively narrower and finer time-scale. In point of interest, we have, since 1978, entered a period of increased seismic activity in California and increased volcanic activity in the Cascades. During such a period, we change our time frame of emphasis and competence to try to pinpoint where we might expect specific activity to materialize next and to discover whether we can predict it in a really rigorous and precise way which can assist in providing for public safety.

Today, you may hear me misplace the term "earthquake" for "volcanic activity" several times. There are several reasons for this. One is that in California we have placed increased emphasis, in the last year and a half, on improving our understanding of seismic activity and the way in which we will manage any predictive capability that we may have. A multi-disciplinary Governor's Task Force has been set up to deal with both scientific issues and the public safety and social issues. In addition, in southern California, we have a southern California Earthquake Preparedness Project which is jointly funded by the state and federal governments. It is looking very closely at means of developing preparedness plans in southern California to deal with earthquake prediction as well as preparedness for the event itself -- something which we in the United States have not really put very much emphasis on. I just returned a few weeks ago from Japan with a group from the Southern California Project. We were interested in the approach being used there, particularly in the Tokai area, which lies west of metropolitan Tokyo, both for preparedness for the prediction and scientific means of making the prediction. We have a conference right now in Monterey

---

* Sherburne, R.W., 1980, Mammoth Lakes, California Earthquakes of May 1980: California Division of Mines and Geology, Special Report 150.

to capture the benefits of that analysis. Unfortunately, I had to leave it last night because of this workshop. Both subjects are fresh in my mind, and they are related, so if I say "earthquake" when I should be saying "volcanic," I hope you will forgive me; they forgave me in Monterey for saying "volcanic" when I should have been saying "earthquake." This is a most interesting stage in human social development in that we have opportunities to bring the social, the public policy, and the research aspects of science together. I would submit this development is timely because of the apparent increase in seismic activity and volcanic activity in the region in which we live.

The way we have structured this workshop is something of a compromise. During the first day, we will be emphasizing the scientific activity and trying to appraise the status of our understanding of volcanic activity in California and some of the implications learned at the active laboratory model of Mount St. Helens. We intended to set this up in such a way that, during that discussion, participants of nonscientific backgrounds can absorb a reasonable part of the discourse and gain an understanding of the uncertainty that scientists have at the boundary between what is known and what we would like to know. Not many lay people really have that understanding sufficiently; so, when they look to the scientific community for advice in an emergency, perhaps they expect more rigorous conclusions and greater unanimity among the scientific community than is reasonable. This workshop, then, really gives them an opportunity to understand both our discord and our discourse.

On the second day, we will be taking the benefits of the social science presentations, which Dr. Gilbert White will introduce this evening, and we will try to correlate those with some of the experiences expressed by those who have experienced the Mount St. Helens activity from an emergency response point-of-view. The public officials and behavioral scientists will relate their experiences and recommendatons regarding volcanic hazards, and we earth scientists will gain important insights into their needs and operation problems. We will be able to consider the implication of the potential for disaster on social behavior from a scientific point-of-view, and then, what the implication of all these things are in terms of developing public policy in California to cope with the circumstance. I think that's a very big menu, indeed, to undertake, but it is one which we look forward to for the increased insights to be derived.

We will be publishing proceedings of this workshop which will highlight the various discussions. Either a text submitted by the authors or one prepared by some of us who are working on the workshop, with the concurrence of the author will be published.

We will be providing in this compromise less time for discussion than I would ideally like to see. In the summer, when we planned this meeting, we considered having a more informal three-day workshop, but it was difficult for us to assess whether our contributing participants would have enough time for a three-day meeting. We didn't want to have people drifting in and out. Consequently, we decided on a comprehensive, but compact, two-day meeting. By doing that, we sacrificed the workshop format, so we are going to have to live with panel discussions and informal discussions as a means of highlighting what we feel are the significant points of the more formal presentations.

To assist in the panel discussions, we've assembled a list of questions to guide the panel discussions. Session I will examine the scientific implications of the volcanologic work done so far within the state and discuss where we should develop priority for our highest attention today. I know there are people here who have differing opinions, and this is something that we want to explore. Additionally, we will be looking at the roles of various scientific groups. What kind of expectations can we have from one group as opposed to another? How can we supplement our activities and enhance our total productivity?

Panel II will deal with questions that are related to making the best use of our social science research and trying to find better means for interaction between the scientific community and the people who are responsible for public safety of our citizens. Then, recommendations will be considered for future emphasis, future work, and how we can work together to accomplish continued growth in our capability of understanding volcanic activity in California and the policy implications of this activity.

I will close by recounting an experince that I had with Alex Cunningham, who is the Director of the California Office of Emergency Services. During the course of the Mammoth Lakes earthquake sequence in May 1980, we had several discussions of volcanic activity that might result in relation to the seismic swarm east of Mount Shasta in the Stevens Pass* area in 1979. We had a portable array of network instruments in the Mammoth Lakes area following the beginning of swarming there in the fall of 1979. After having a rapid sequence of three magnitude 6 events -- which, viewed in the context of the previous twenty years experience of seismicity in California, represented an alarming increase in rate of significant events concentrated in an area of recent volcanic activity -- it was necessary for us to develop a strategy for public safety there. We extemporaneously improvised an arrangement by which the Office of Emergency Services, in conjunction with the National Guard, prepared to provide emergency communications and emergency medical supplies for that area if a magnitude 7 earthquake or similar geologic event took place. That underscored, for both Alex and myself, the fact that the matter of dealing with public safety and scientific advice in public policy was something we needed to expand and explore.

We look forward to getting better acquainted with those of you who have insight to share in this important role. I want to welcome you again to our workshop, and I hope that you will have a sense of accomplishment as I am sure I will at the end of that time.

---

* Bennett and others, 1979, Stephens Pass Earthquakes: California Geology, Feb. 1979, p. 217-234.

POTENTIALLY ACTIVE VOLCANIC ZONES IN CALIFORNIA

Charles W. Chesterman, Senior Scientist (retired)
California Division of Mines and Geology
and
Curator of Mineralogy, California Academy of Sciences
San Francisco, California

ABSTRACT

Volcanic activity has played a dominant role in California's long geologic history. Records in rocks of many ages demonstrate that volcanic activity commenced in the Precambrian as early as 1.7 billion years ago, and has continued almost continuously into the present century. A review of the Geologic Map of California is sufficient to indicate the widespread distribution of volcanic rocks and source areas, except in the Great Valley, where the cover of soils and sedimentary rocks may mask other possible volcanic centers.

Advances in geophysics and geochemistry have demonstrated the close relationships between zones of volcanic activity and movements of tectonic blocks. Zones of volcanic activity in the Cascade Range and the Coast Range provinces in California can be explained through a subduction mechanism, whereas similar zones in the Mono Basin-Long Valley region of Mono County, the Modoc Plateau Province, and elsewhere in the Mojave Desert and Colorado Desert provinces owe their origins to the combined effects of plate tectonics and block faulting of thin continental crust.

Five active volcanic zones in California include Mount Shasta, Lassen Peak, and Medicine Lake Highland, all in the Cascade Range Province, the Mono Basin-Long Valley region of Mono County, and the Cima volcanic field in San Bernardino County. A significant number of documented eruptions has occurred in these areas in the last 2,000 years. The above named active volcanic zones and 18 other volcanic zones whose latest eruptions are known (or presumed) to be Quaternary in age, but had not erupted in the last 2,000,000 years, constitute the known potentially active volcanic zones in California.

INTRODUCTION

Volcanism has been very active and prominent almost continuously throughout California's geologic history, commencing as early as 1.7 billion years ago in the Precambrian and extending into the twentieth century. It has manifested itself through the extrusion of tremendous volumes of volcanic rocks as lava flows and fragmental deposits, and the intrusion of dikes, domes, plugs, and sills.

Time and the erosive forces of running water, moving ice and air, and of gravity have obliterated much of the evidence of volcanic activity, but thick deposits of metamorphosed volcanic rocks, of which some are greenstones and others, schists, form prominent geologic units ranging in age from early Paleozoic through late Mesozoic (an interval of some 500 million years) in the Sierra Nevada, the Klamath and Siskiyou mountains, the Coastal Ranges of California, and the Mojave Desert.

In order to illustrate in a modest way the extent of volcanic activity in California, one need only examine carefully the northeastern part of the state, which includes all of Modoc County and significant parts of Lassen, Plumas, and Siskiyou

counties. This is an area of approximately 12,000 square miles, one-thirteenth of the area of California, which is underlain by volcanic materials ranging in age from Miocene to Holocene. Much of these volcanic rock materials, totaling approximately 2,400 cubic miles, were deposited through explosive volcanic eruptions.

Very rarely indeed is volcanic activity an isolated earth process unrelated to other forces at work in the Earth's crust. On the contrary, it can be demonstrated that volcanic activity is and has throughout the Earth's long geologic history been closely associated with earthquakes, mountain building processes, and lastly and more recently, through the interaction of gigantic plates that comprise segments of the Earth's crust.

Volcanic activity in the Cascade Range and Coast Range provinces in California is best explained through the interaction between the Pacific plate and the North American plate, in which portions of the former being subducted beneath the North American plate are remelted and rise along zones of weakness to the Earth's surface to result in volcanic activity. Volcanic activity in the Basin and Range Province in California, which includes the Modoc Plateau-Warner Range area in Modoc County, the Mono Basin-Long Valley region of Mono County, and the Mojave Desert and Colorado desert regions in southeastern California, is probably due to a combination of the interaction of Earth plates and the block faulting of thin continental crust on the margin of an area undergoing extension.

ZONES OF VOLCANIC ACTIVITY IN CALIFORNIA

Another look at the Geologic Map of California tells one that the state has been mapped geologically one way or another, but it is not possible to identify all deposits of quaternary volcanic rocks since: (1) geologic process do not stop conveniently at temporal or spatial boundaries; (2) geological mapping is incomplete or even totally lacking for certain areas of the state; and (3) techniques of geochronology, although gaining stature and becoming more reliable all the time, are still not sufficiently advanced as to allow clear and reliable dating of all rocks. Because of these factors, deposits of quaternary volcanic rocks may be omitted or incorrectly dated on the map, and in some cases rocks of other ages may be labeled Quaternary.

A significant amount of data, however, is readily available, and many deposits of volcanic rocks in California can be identified as being of Pleistocene and Holocene ages. Holocene is here defined to include events since the latest glacial (Tioga) stage. This is a variable time span representing, perhaps, 6,000 to 10,000 years. The traditional 1,000,000 year date for the beginning of the Pleistocene has been pushed back to 2,000,000 years, and in some cases further still. For rock units of approximately this age, I am using here, for convenience, a Plio-Pleistocene time interval. This is a convenient slot for many volcanic rock units in California which are not yet precisely dated.

Following Kilbourne and Anderson (1981), zones of volcanic activity in California can be considered in three categories: (1) active -- one in which there is current volcanic activity, or which has erupted in the last 2,000 years; (2) potentially active -- one known (or presumed) to be Quaternary in age, but the most recent eruption has not been dated as being less than 2,000 years ago; and (3) inactive -- one in which there has been no eruption in the last 2 million years.

Since our interest for this workshop lies in the active and potentially active volcanic zones in California, discussion will be confined to 23 areas in the state in which rocks of Pleistocene and especially Holocene ages occur. Frequent reference will be made to Figure 1, a map of California which shows the areas of known deposits of Quaternary volcanic rocks, and also several major tectonic features, particularly faults, as they may relate to zones of Quaternary volcanic activity.

MAP OF CALIFORNIA SHOWING AREAS UNDERLAIN BY QUATERNARY VOLCANIC ROCKS—THE POTENTIALLY ACTIVE VOLCANIC ZONES

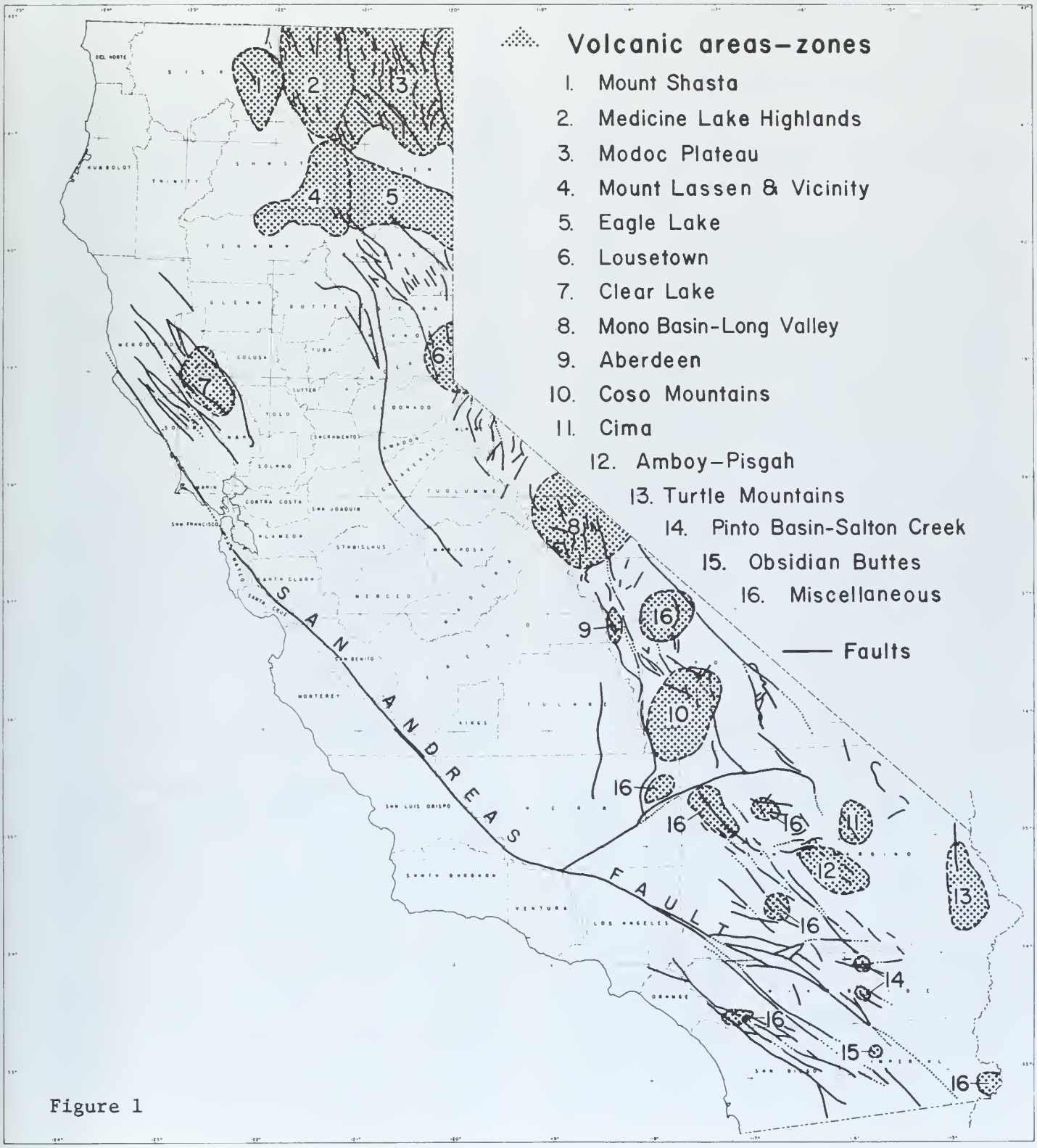


Figure 1

POTENTIALLY ACTIVE VOLCANIC ZONES IN CALIFORNIA

The following discussion will consider the potentially active volcanic zones in California, their geographic locations, types of volcanic products, and physical features, and will commence with those zones in the northern part of the state and conclude with a group of miscellaneous small zones that are largely in southeastern California.

Mount Shasta (Area 1). Mount Shasta, a complex stratocone and the largest of the Cascade volcanoes, is in the central part of Siskiyou County. It is composed of Pleistocene andesite and basalt flows, and pyroclastic deposits, and Holocene basalt and andesite flows, dacite domes and pyroclastic deposits. A major north-south fracture zone that passes through the volcano, has controlled the location of cinder cones and plug domes. Shastina, a Holocene cone high on the west flank of Mount Shasta, contains a central plug dome of dacite, and was the source of voluminous pyroclastic-flow deposits that cover many square miles on the west side of Mount Shasta and reach points beyond the town of Weed. Similar pyroclastic-flow materials issued forth from Black Butte, a composite of four dacite domes of Holocene age, and were deposited to the southwest as far as Lake Siskiyou. There are 13 Quaternary cinder cones, remnants of five Pliocene cinder cones, and Holocene flows from Shastina and Hotlum cones. Perhaps the most recent eruption in the area occurred in 1786.

Medicine Lake Highland (Area 2). Medicine Lake Highland is in eastern Siskiyou County and western Modoc County. The highland is a rampart of small volcanoes ranging from late Pleistocene to Holocene in age perched upon a low, broad-shield volcano of Pliocene and Miocene basalt and Pleistocene pyroclastic deposits. The lava flows and pyroclastic deposits of the cone were intruded by rhyolite, and collapse of the central part of the cone along a set of arcuate fractures, gave rise to a caldera which now contains Medicine Lake. Violent eruptions in Holocene time (660 A.D. $\pm$ 240 years) resulted in the mantling of the area by rhyolitic pumiceous tephra -- deposition of which was followed by the emplacement of obsidian domes and the development of cinder cones. More than 100 cinder cones developed during the Holocene volcanic episode, and at least 20 cones during the Pleistocene.

Modoc Plateau (Area 3). This area is wholly in Modoc County and includes the Warner Range. It has been the focus of intensive volcanism since the Miocene. In 1954, there was a violent mud-volcano eruption on the east side of the Warner Range near Lake City. Numerous basaltic cinder cones dot a plateau-like surface that is underlain by numerous flood basalt flows.

Mount Lassen and Vicinity (Area 4). Although Lassen is in Shasta County, the general area herein considered is largely in eastern Shasta County but includes small portions of adjacent Lassen, Plumas, and Tehama counties. The area was the site of extensive out-pourings of basalt and andesite flows during the Pliocene and Pleistocene. Later, a large stratocone named "Mount Tehama" developed as the result of subsequent volcanic activity. Much later, rhyolite and dacite intruded the flanks of Mount Tehama, flows of dacitic lava erupted from vents near Lassen Peak and, much later still, the dacite plug dome which forms Lassen Peak was emplaced. The eventual collapse of Mount Tehama formed a caldera in which one can now find hot springs and extensive fumarolic action.

During the Holocene, perhaps not more than 1,200 years ago, violent eruptions blasted forth from an eruptive center north of Lassen Peak and produced hot pyroclastic-flows and pumiceous tephra. Shortly thereafter, a group of dacite domes, now called Chaos Crags, were emplaced in the same eruptive center.

In 1851-52, an eruption of quartz basalt lava, a few miles northeast of Lassen Peak, gave rise to a volcanic cone (called Cinder Cone) and lava flows. More recent activity in the Mount Lassen area, commencing in

1914 and culminating in 1917, was of the explosive type and is very well documented.

There are over 30 cinder cones of Plio-Pleistocene age in the area, and current activity is restricted to hot springs and fumaroles.

Eagle Lake (Area 5). This area lies almost wholly in Lassen County, and is underlain by numerous flood basalt flows of Pliocene and Holocene ages. The latest eruptions of, perhaps, Holocene age were basaltic lava flows in the vicinity of Eagle Lake. At least 30 cinder cones of Quaternary age occur in the area.

Lousetown (Area 6). This area occurs north of Lake Tahoe and is in the eastern parts of Nevada and Placer counties. It is underlain largely by flows of basalt and latite of early Pleistocene age, which are said to have a K/Ar age of 1-2 million years B.P. There were explosive eruptions in the area as evidenced by remnants of eight cinder cones.

Clear Lake (Area 7). The Clear Lake volcanic field is in southern Lake County and northeastern Sonoma County. It includes the well-known Geysers geothermal field. Flows of basalt, andesite and rhyolite, and rhyolitic tuffs of Pleistocene age occur in the area. Rocks of Holocene age include obsidian, andesite, dacite, and four cinder cones. The occurrence of sulfur and extensive mercury mineralization at Sulphur Bank; deposits of sulfur on Mount Konocti; and the high concentration of boron at Borax Lake all indicate recent volcanic activity. The hot springs, fumaroles, and steam wells at the Geysers and vicinity are clear indications that a significant source of heat, which is undoubtedly related to volcanic action, is still present in the area.

Mono Basin-Long Valley (Area 8). This area of high potential volcanic activity occurs largely in Mono County. Cenozoic volcanic rocks of Oligocene and Miocene ages (radiometrically dated as 11 to 29 million years old) include andesite, dacite, rhyolite, and welded tuff. Between 3 and 12 million years ago, discontinuous volcanic activity resulted in the eruption of andesite, basalt, rhyolite, and pyroclastic deposits. The Pleistocene was a period of almost continuous volcanic activity extending to the present. A major eruption about 700,000 years ago gave rise to the Bishop Tuff and the formation of Long Valley caldera. The Mono Basin-Long Valley region has experienced at least 30 pumiceous tephra and lava eruptions in the past 2,000 years, and all were of silicic lavas. Many hot springs and several steam wells occur at and near the Casa Diablo thermal area, and the latest eruption may have taken place beneath the waters of Mono Lake as late as 1890.

Aberdeen (Area 9). The Aberdeen volcanic field is in Owens Valley at the base of the Sierra Nevada in west-central Inyo County. It contains flows and cones of basalt of Holocene or late Pleistocene age, and a dome of perlitic rhyolite of Pleistocene age, all of which lie partly on alluvium.

Coso Mountains (Area 10). The Coso Mountains are at the southern end of Owens Valley in Inyo County. This area has been the site of explosive volcanic eruptions starting some 11 million years ago and culminating about 40,000 years ago. There are 35 rhyolite domes, 19 basaltic cinder cones, and significant deposits of pumiceous tephra lying on or near the surface of the ground. Current activity includes fumaroles and hot springs at the Coso Hot Springs thermal area.

Cima (Area 11). The Cima volcanic field, located in the northeastern part of San Bernardino County, contains basaltic cinder cones and lava flows of Pleistocene age, and lava flows as well as 27 cinder cones of Holocene age. The Holocene cones and lava flows rest on alluvium, and the youngest of the Holocene rocks has been dated at about 360 years.

Amboy-Pisgah (Area 12). This area is in the central part of San Bernardino County and centers principally about Pisgah Crater and Amboy Crater, which are separated by some 40 miles of arid lands. Holocene basaltic cinder cones and lava flows, and Pliocene andesitic and basaltic dikes, lava flows, plugs and sills occur in the region.

Because of the fresh appearance of their lavas, Amboy and Pisgah craters are thought to be less than 2,000 years old.

Turtle Mountains (Area 13). The Turtle Mountains, which contain flows of Pleistocene basalt lying on late Tertiary volcanic rocks, are in the southeastern part of San Bernardino County. The late Tertiary volcanic rocks contain layers of pyroclastic deposits and perlitic rhyolite flows, which indicate that the area has been the focus of explosive volcanic eruptions.

Pinto Basin-Salton Creek (Area 14). Remnants of Pleistocene or Holocene basaltic flows and pyroclastic deposits lie on alluvium in the Pinto Basin and Salton Creek areas in central Riverside County.

Obsidian Buttes (Area 15). This area, in Imperial County near the southern end of Salton Sea, contains obsidian domes and pumiceous tephra deposits of late Pleistocene age amid alluvium and lacustrine sediments. The area contains hot springs, carbon dioxide springs and wells, and mud volcanoes. Several thermal wells encountered hot brines.

Miscellaneous (Area 16). Scattered throughout the Basin and Ranges Province in Inyo, Imperial, Kern, Riverside, San Bernardino, and San Diego counties are a number of bodies of volcanic rocks, consisting principally of flows of andesite and basalt, and pyroclastic materials, all ranging in age from late Pliocene to Holocene. Included among the bodies are: lavas in the El Paso Mountains in eastern Kern County; basaltic flow remnants on pyroclastic deposits in the Fort Irwin area and at Opal Mountain, northeast and northwest of Barstow respectively; small remnants of a probable Pleistocene basalt flow northeast of Ogilby, Imperial County; and possible Pleistocene basalt flows on pyroclastic deposits near Murrieta, Riverside County.

An extensive area in central Inyo County contains flows and pyroclastic deposits of Pliocene and/or Pleistocene age, as well as a Holocene basaltic cinder cone and rhyolitic ash deposits.

CONCLUSIONS

The above listed areas contain the known, potentially active volcanic zones in California wherein hazardous conditions are most likely to occur. However, one cannot be absolutely certain that this list is complete, for, as was stated earlier, there is a likelihood (remote as it may be) that there are isolated bodies of Holocene volcanic rocks that have been erroneously included among older volcanic units. These improperly identified bodies might just as well be sites for future volcanic activity as are any of the five zones that are considered among the most active in the state.

DISCUSSION

McBirney: I notice that the Sutter Buttes were not mentioned in your talk. Do you consider them too old, and if so, what is the youngest age that has been obtained there?

Chesterman: I didn't mention them as being active because they are rather old. I believe their youngest age is about 1.4 million years old.

Question: What is the approximate age of the volcanic tubes at Cambria, north of Morro Bay?

Chesterman: Any volcanism in that part of the state is likely to be either late Miocene or early Pliocene in age. As one proceeds from the southern part of the California Coastal Ranges northward, the age of volcanic rocks becomes progressively younger. Volcanic rocks in the Morro Bay area are of late Miocene/early Pliocene age while to the north, in Lake County, some volcanic rocks are as young as very late Pleistocene, or about 11,000 years old.

Question: Just how active is the Surprise Valley area? I heard about a mud volcano being in that area. Could you explain that?

Chesterman: Mud volcanoes erupted in Surprise Valley at hot springs near Lake City, Modoc County in 1951 and 1953. There is extensive faulting in the area, and although the springs owe their high temperature of about 65°C and part of their water supply and mineral content to past volcanism, it seems unlikely that their mud-volcano activity of comparatively recent date is a forerunner of future volcanic activity.

Question: How about the Aberdeen area?

Chesterman: The Aberdeen volcanic area is located in Inyo County along a frontal fault zone of the Sierra Nevada. It is an area where rocks of both rhyolitic and basaltic compositions erupted from nearby vents. The basaltic eruptions formed cinder cones and lava flows while the rhyolitic eruptions have given rise to domes of perlitic rhyolitic and tuffs. A late Pleistocene or early Holocene age has been determined for one of the cinder cones.

REFERENCES

Alfors, J.T., 1980, Regional geology of the Mammoth Lakes region, California, in Sherburne, R.W., editor, 1980, Mammoth Lakes, California earthquakes of May 1980: California Division of Mines and Geology Special Report 150, p.1-6.

Anderson, C.A., 1941, Volcanoes of the Medicine Lake Highland, California: California University Department of Geological Sciences Bulletin, v. 25, p. 347-421.

Bailey, Roy A., Dalrymple, G. Brent, and Lanphere, Marvin A., 1976, Volcanism, structure, and geochronology of Long Valley Caldera, Mono County, California: Journal of Geophysical Research, v. 81, n. 5, p. 725-744.

Birkeland, Peter W., 1963, Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California: Geological Society of America Bulletin, v. 74, p. 1453-1464.

Chesterman, Charles W., 1971, Volcanism in California: California Geology, v. 24, p. 139-147.

Chesterman, Charles W., 1955, Age of the obsidian at Glass Mountain, Siskiyou County, California: American Journal of Science, v. 253, p. 418-424.

Crandell, D.R., Mullineaux, D.R., Sigafoos, R.S., and Rubin, M., 1974, Chaos Crags eruptions and rockfall-avalanches, Lassen Volcanic National Park, California: Journal of Research of the U. S. Geological Survey, v. 2, n. 1, p. 46-60.

Dickinson, W.R., 1979, Cenozoic plate tectonic setting of the Cordilleran region in the United States, in Armentrout, John M., Cole, Mark R., and TerBest, Harry Jr., editors, 1979, Cenozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists, Los Angeles, p. 1-13.

Finch, R.H., 1930, Activity of a California volcano in 1786: The Volcano Letter, n. 308, p. 3.

Harkness, H.W., 1975, A recent volcano in Plumas County: California Academy of Science, Proceedings, v. V, 1873-1874, p. 408-412.

Katz, Marvin, and Boettcher, Art, 1980, The Cima volcanic field, in Fife, D.E. and Brown, A.R., editors, 1980, Geology and mineral wealth of the California Desert: South Coast Geological Society, Santa Ana, p. 236-241.

Kilbourne, R.T. and Anderson, C.L., 1981, Volcanic History and "active" volcanism in California: California Geology, v. 34, p. 159-168.

Kilbourne, R.T., Chesterman, C.W., and Wood, S.H., 1980, Recent volcanism in the Mono Basin-Long Valley region of Mono County, California, in Sherburne, R. W., editor, 1980, Mammoth Lakes, California earthquakes of May 1980: California Division of Mines and Geology Special Report 150.

Parker, Ronald B., 1963, Recent volcanism at Amboy Crater, San Bernardino County, California: California Division of Mines and Geology Special Report 76.

Proffett, John M., Jr., 1977, Cenozoic geology of the Yerington District, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247-266.

Rinehart, C. D., and Huber, N. King, 1965, The Inyo Crater Lakes--a blast in the past: California Division of Mines and Geology Mineral Information Service, v. 18, n. 9, p. 169-172.

Shelton, John S., 1954, Miocene volcanism in coastal southern California: California Division of Mines Bulletin 170, ch. VII, p. 31-36.

Townley, S.D., and Maxwell, W.A., 1939, Descriptive catalogue of earthquakes of the Pacific Coast of the United States: Seismological Society of America Bulletin, v. 29, p. 83.

White, Donald E., 1955, Violent mud-volcano eruption of the Lake City hot springs, northeastern California: Geological Society of America Bulletin, v. 66, p. 1109-1130.

Williams, Howel, 1932, Mount Shasta, a Cascade volcano: Journal of Geology, v. 40, p. 417-429.

Williams, Howel, 1932, Geology of the Lassen Volcanic National Park, California: California University Department of Geological Science Bulletin, v. 22, p. 193-385.

Williams, Howel, 1949, Geology of the Macdoel quadrangle, California: California Division of Mines Bulletin 151.

OTHER POTENTIAL ERUPTION CENTERS IN CALIFORNIA: LONG VALLEY-MONO LAKE, COSO, AND CLEAR LAKE VOLCANIC FIELDS

Roy A. Bailey
U. S. Geological Survey
National Center 951, Reston, VA 22092

ABSTRACT

Geologic and geophysical evidence indicate that the Long Valley-Mono, Coso, and Clear Lake volcanic areas are underlain by molten magma chambers, are in regions of unusually high seismic and tectonic activity, and have been the sites of frequent volcanism in the recent geologic past. Collectively, these facts suggest that volcanic eruptions can be expected to continue in these areas well into the future. The important questions are when, where, what kind, and what magnitude?

Long Valley caldera has been intermittently active for 2 million years. Eruptions have been predominantly rhyolitic, with major episodes occurring at 200,000-year intervals (0.9, 0.7, 0.5, 0.3, and 0.1 million years ago), most recently in the western caldera moat. Although this periodicity suggests that possible future eruptions may be 100,000 years away, recent, unusually strong, and puzzling seismic activity (1975-1981), accompanied by unprecedented uplift of the caldera floor, suggests that residual magma in the Long Valley chamber may be rising in response to tectonic stresses, thereby increasing the potential for an eruption. The nearby Mono-Inyo Craters have been active for 40,000 years, and for the past 1,500 years have erupted regularly at 200 to 300 year intervals. Because the last eruption was about 250 years ago, the potential for an eruption in the next 50 years is high.

The Coso area includes 19 basaltic cinder cones and 38 rhyolite domes. It erupted between 1.1 million years and 40,000 years ago. Time-volume relations suggest that a basaltic eruption could occur within a few thousand years, whereas a rhyolitic eruption is unlikely for 60,000 years (Bacon, 1981).

The Clear Lake volcanic area has been episodically active for 2 million years, erupting widespread basalt and andesite 2.0-1.3 million years ago, and basalt and minor rhyolite 0.1-0.01 million years ago. The general focus of eruptions has migrated with time from Pine Mountain northward to the eastern shores of Clear Lake. Future eruptions could be rhyolitic, but basaltic ones are more likely. Available age data do not permit prediction of the time (Hearn, 1981).

INTRODUCTION

These three volcanic fields -- Clear Lake, Coso, and Long Valley-Mono Lake -- have the capacity to provide great economic benefits for the state, yet paradoxically they also have the potential for doing great harm. All three fields are underlain by silicic magma chambers which conduct large amounts of heat to the surface, thus making possible their exploitation for geothermal energy. The Geysers geothermal field, near Clear Lake, presently generates about 1,000 megawatts of electrical power -- energy greater than that used by the City of San Francisco; and both the Long Valley and Coso fields are currently under commercial geothermal exploration. However, these energy-producing magma bodies are also potentially capable of producing the most

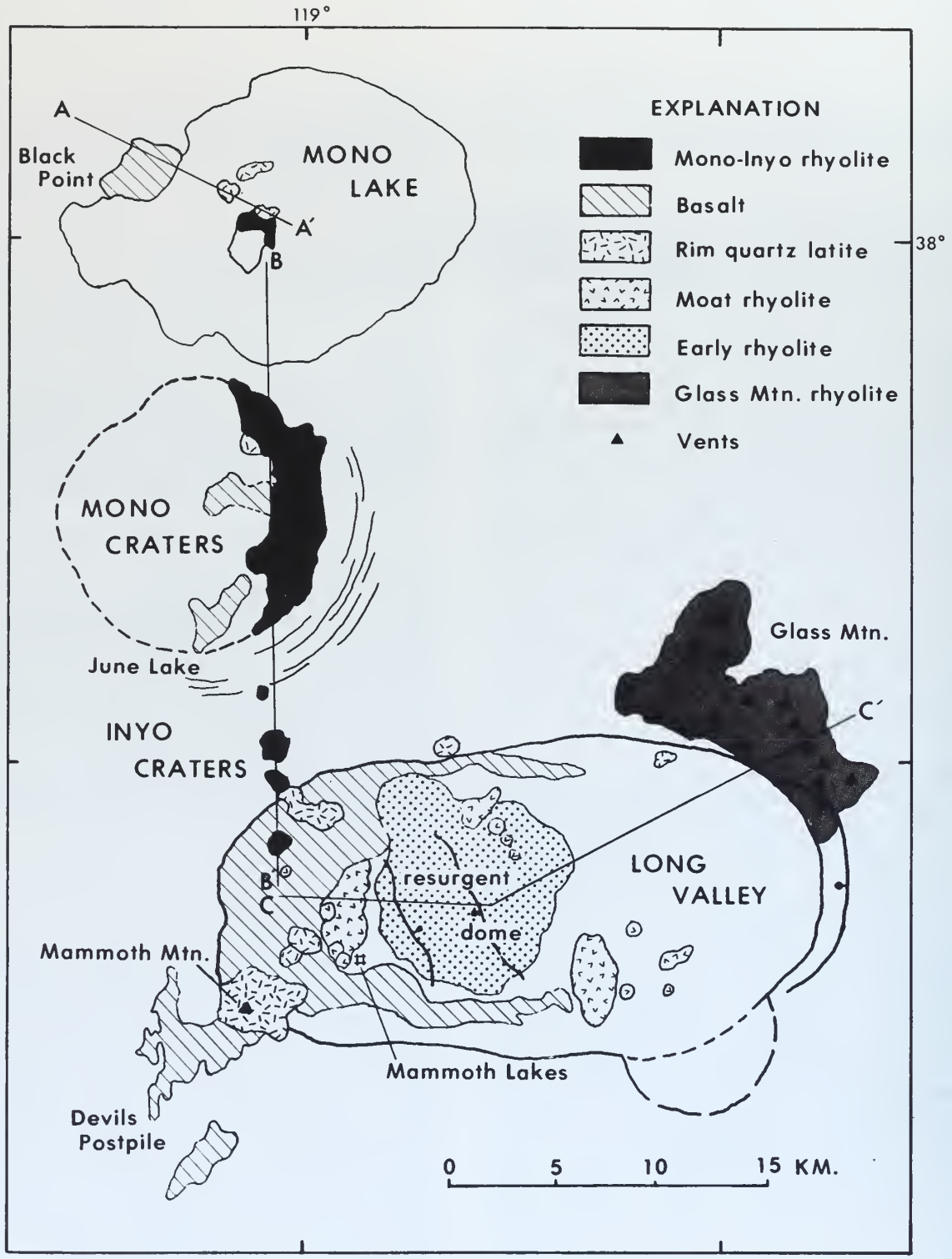


Figure 1. Geologic map of Long Valley-Mono Lake volcanic area. Lines A-A^1, B-B^1, C-C^1 show approximate location of composite cross section of Figure 2.

explosive and devastating types of eruptions known to mankind. Fortunately, such eruptions occur very infrequently. Nevertheless, such volcanic systems are extremely dangerous and eruptions from them are not readily predictable on the basis of current knowledge.

LONG VALLEY-MONO LAKE REGION

Volcanism. The Long Valley-Mono Lake region is in east-central California between the White Mountains and the crest of the Sierra Nevada at the north end of the Owens Valley Rift. The region includes three separate, but possibly interconnected volcanic complexes (Bailey, 1980): the Long Valley caldera complex; the Mono-Inyo Craters chain; and the volcanic islands of Mono Lake (Figure 1).

The Long Valley complex includes the following salient features (Bailey, Dalrymple, and Lanphere, 1976).

a. Glass Mountain -- a large pre-caldera rhyolite com- plex on the northeast rim of Long Valley caldera.

b. Long Valley caldera -- a 450 km^2 elliptical volcanic depression about 30 kilometers east-west by 20 kilometers north-south.

c. A resurgent dome -- a 75 km^2 uplifted area in the west-central part of the caldera.

d. Post-caldera rhyolitic flows and domes in the caldera moat and on its rim, concentric around the resurgent dome.

Volcanism in the Long Valley area began about 3.5 million years ago, with widespread eruption of basaltic lavas. Erosional remnants of this basaltic field are scattered over a 4,000 km^2 area in the Adobe Hills, around the periphery of Long Valley caldera, and in the High Sierras, suggesting an extensive mantle source area for these eruptions. Associated quartz latites and andesites of about the same age are found locally along the north and west rims of the caldera, and probably represent the onset of magmatic differentiation that eventually culminated in formation of the Long Valley magma chamber. The Glass Mountain rhyolite complex, which formed along an incipient arcuate ring-fracture on the northeast border of the present caldera between 1.9 and 0.9 m.y. ago, appears to represent the earliest leakage of magma from the early, highly fractionated, Long Valley magma chamber.

Climactic eruptions formed Long Valley caldera about 700,000 years ago, when the roof of the subjacent magma chamber ruptured and 600 km^3 of rhyolite ash and pumice was expelled mainly as ash flows. These pyroclastic deposits, mapped as the Bishop Tuff, inundated over 1,500 km^2 in upper Owens Valley, Adobe Valley, and Mono Basin; flows even spilled across the Sierra Nevada into the drainage of the San Joaquin River, possibly reaching the edge of the Great Valley. Recent drilling within the caldera has penetrated 1,500 m of Bishop Tuff, demonstrating that a large volume of this deposit also fills the caldera and is buried beneath younger post-caldera lavas and sediments.

After collapse of the roof of the magma chamber, eruptions continued intermittently on the caldera floor. Early post-caldera tephra eruptions were followed by hot, fluid obsidian flows; at the same time, renewal of magma pressure uplifted the western half of the caldera, arching the floor into a resurgent structural dome about 10 km in diameter. This resurgent dome formed within the relatively short time of 50,000 to 100,000 years and was probably caused by isostatic rebound as a consequence of eruption of the large volume of Bishop tuff.

Later, several lower-temperature, viscous, crystal-rich rhyolite flows and domes, probably representing the onset of crystallization of the chamber, erupted in the caldera moat peripheral to the resurgent dome. Eruption of these moat rhyolites occurred at 200,000-year intervals: the first episode occurring about 500,000 years ago on the north flank of the resurgent dome; the second, 300,000 years ago in the southeast moat; and the last, 100,000 years ago in the west moat. This 200,000-year recurrence interval for the moat rhyolites would suggest that the next moat episode

might be another 100,000 years hence. Mammoth Mountain, a large cummulo-volcano on the southwest rim of the caldera, consisting of 20 or more steep-sided quartz latite domes and flows, began erupting about 150,000 years ago and was active until 50,000 years ago. Several other similar, but much smaller rim volcanoes occur on the northwest and north rim of the caldera. The 50,000-year period of quiescence since the last dome eruption on Mammoth Mountain would suggest that it may be extinct. Its eruption frequency between 150,000 and 50,000 years ago was on average one per 5,000 years. Yet 500 years ago, a steam blast eruption occurred on its north slope about 1 km west of the Mammoth Mountain Ski Lodge, and active fumaroles persist at several localities on the mountain.

Projection of possible future activity at Long Valley is complicated by the more recent initiation of overlapping volcanism related to the Mono Craters and Mono Lake complexes.

Eruptions related to the Mono complexes began about 200,000 years ago with extrusion of basaltic lavas along a 50-km north-south zone extending from the Devils Postpile to Black Point on the north shore of Mono Lake (Figure 1). The oldest of these lavas, at Devils Postpile and in the west moat of Long Valley caldera, are between 200,000 and 60,000 years old. Further north is the June Lake cinder cone, probably between 20,000 and 75,000 years old on the basis of glacial stratigraphy (Putnam, 1949; Curry, 1971), and the sublacustrine volcano at Black Point, radiocarbon-dated at about 13,500 years (Lajoie, 1968). The progressive northward decrease in age of centers along this zone suggests that the eruptions followed a northward-propagating fracture system.

Along this same north-south zone erupted the somewhat younger rhyolite domes and flows of the Mono-Inyo Craters. The Mono Craters, an arcuate chain of 30 rhyolite domes, are localized on the mylonitized border of a subcircular Cretaceous pluton (Kistler, 1956). To the east and south an arcuate system of concentric fractures and faults suggests recent development of an incipient ring-fracture zone analogous to that along which the Glass Mountain rhyolites erupted prior to formation of Long Valley caldera. Thus, the Mono Craters may represent precaldera volcanism above a second, actively-forming magma chamber to the northwest of Long Valley (Figure 2).

Eruptions at Mono Craters and their southern extension, the Inyo Craters, began about 40,000 years ago and have continued almost to the present. Volume and age data (Figure 3) based on hydration-rind dating by Spencer Wood (1977) indicate that the rate of lava extrusion has increased dramatically in the past 10,000 years and that during the past 2,000 years eruptions have occurred every 200 - 300 years. The change from porphyritic (crystal-rich) to aphyritic (crystal-poor) lavas in the last 3,000 years suggests either an increase in magma temperature or a decrease in its depth, both of which imply increased potential for eruptions. The last eruption of the Inyo Craters probably occurred less than 400 years ago and possibly as recently as 250 years ago based on radiocarbon dated tephras (Dan Miller, written communication, 1980). Assuming that the frequency of past eruptions is to continue, an eruption from the Mono-Inyo Craters is likely within the next 50 years.

Geophysical studies. Gravity and seismic surveys (Kane and others, 1976; Steeples and Iyer, 1976; Hill, 1976) indicate that a geophysically anomalous crustal mass underlies the Long Valley resurgent dome (Figure 4). Although not conclusive, these studies suggest that this mass is a partially molten magma chamber still capable of erupting. Evidence exists for a separate dikelike mass of magma beneath the Inyo Craters, and it may extend northward and merge with a possible larger magma chamber beneath the Mono Craters. However, geophysical and teleseismic P-wave studies confirming these latter inferences have not yet been completed.

Seismicity and ground deformation. On May 15-27, 1980, coincident with the second major eruption of Mount St. Helens, Washington, the Long Valley area was rocked by four magnitude 6 earthquakes (commonly referred to as the Mammoth Lakes earthquake sequence). For one year

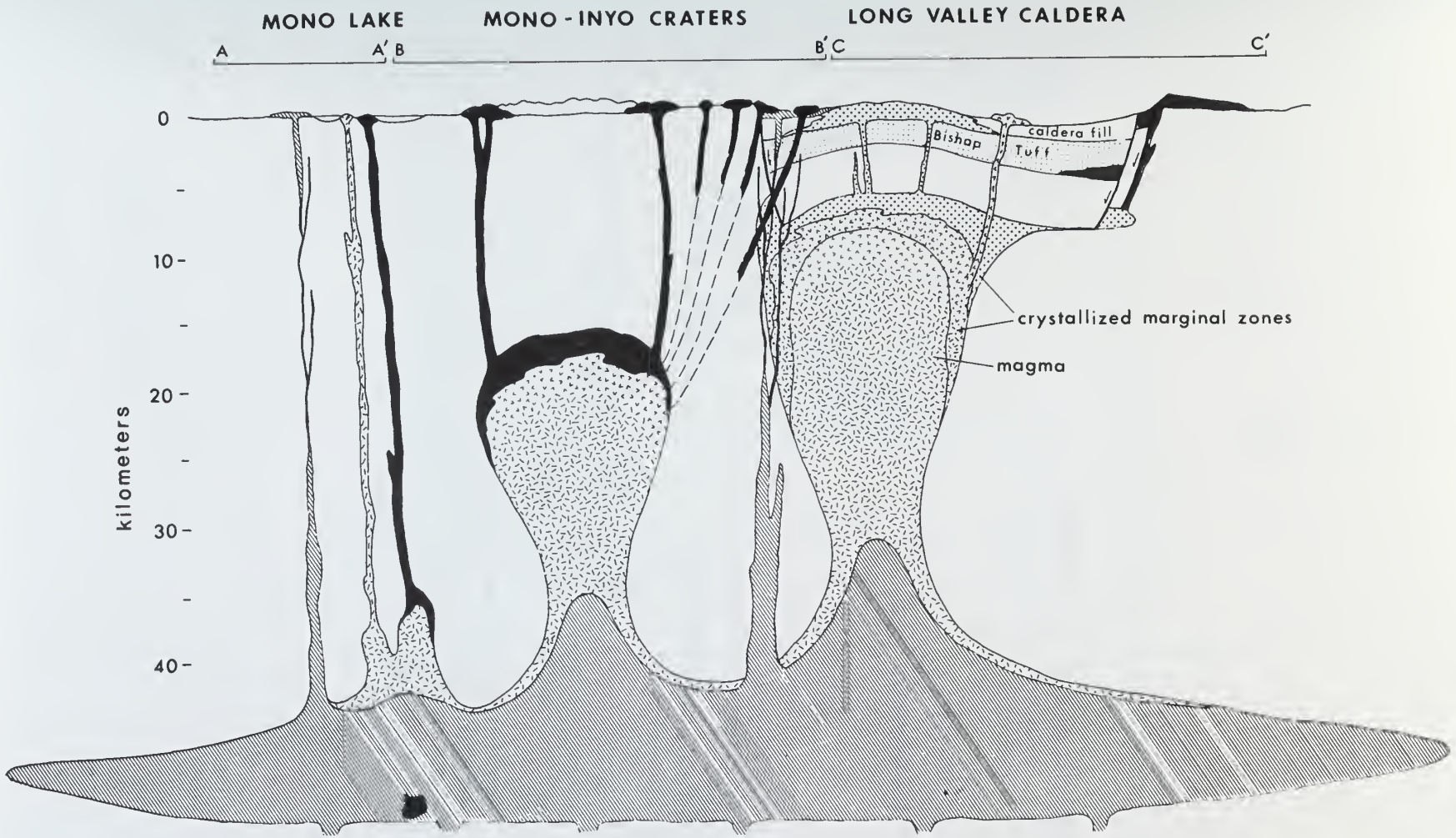


Figure 2. Composite schematic cross section of the Long Valley-Mono Inyo Craters, and Mono Lake volcanic complexes, showing hypothetical configurations of their inferred magma chambers. Segments A-A^1, B-B^1, C-C^1 are located in Figure 1. Ornamentation same as in Figure 1. Vertical and and horizontal scale approximately equal.

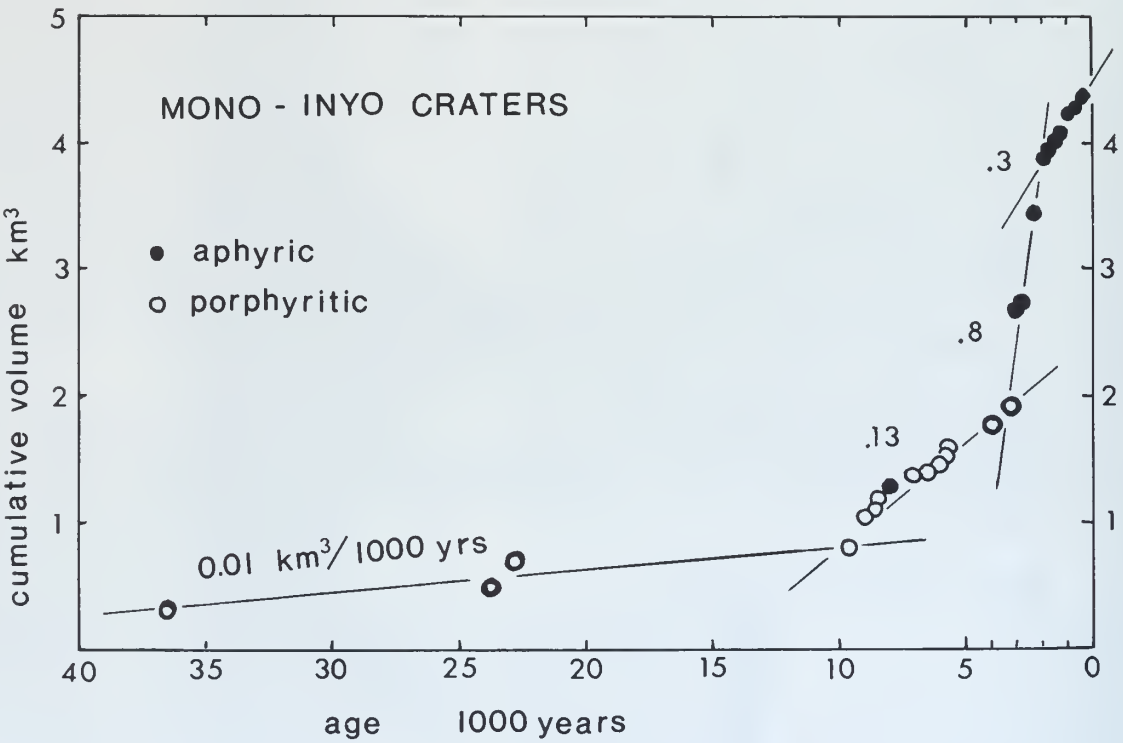


Figure 3. Diagram for the Mono-Inyo Craters showing relation between commulative erupted volume and age. Numbered line segments (e.g., .01 km^3/1000 years) show change in average volumetric eruption rate with time. Maximum eruption rate (0.8 km^3/1000 years) was attained between 3000-2000 years b.p. (Data from Wood, 1977).

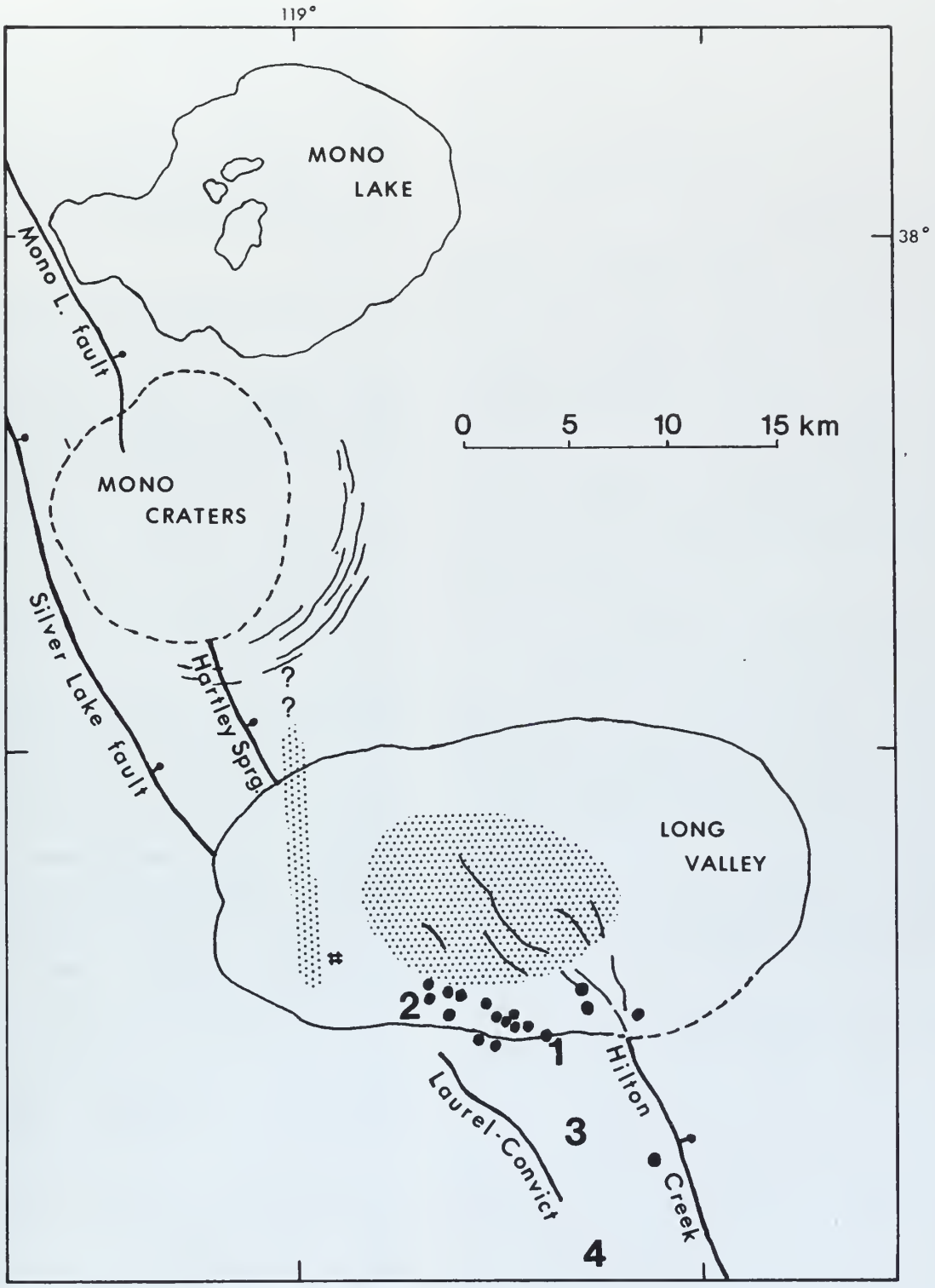


Figure 4. Sketch map showing major Sierran frontial faults and distribution of magma (stippled) at 12 km depth beneath Long Valley caldera, (after Steeples and Iyer, 1976, Figure 6). 1, 2, 3, and 4 are epicenters of successive magnitude 6 earthquakes of the May 25-27, 1980 Mammoth Lakes earthquake sequence. Solid circles are epicenters for quakes $\geq$ 4 between 1 June 1979 to 25 May 1980. (After Cramer and Toppozada, 1980, Figures 4 and 6).

prior to this sequence, seismicity of lesser magnitude was unusually prevalent within and along the south side of Long Valley caldera (Cramer and Toppozada, 1980). Although the seismicity of the area generally has been considered to be of tectonic origin, peculiarities of the most recent seismicity, together with associated unusual ground deformation, suggests an alternative interpretation.

A resurvey in October 1980 of a second order level-line along Route 395, from Tom's Place across the Hilton Creek fault and through Long Valley caldera to Crestview, has revealed unusual ground displacements (Jim Savage and Malcolm Clark, written communication, 1981). Compared with results of a previous 1975 leveling, the resurvey revealed 12 cm displacement (relative west upward) on the Hilton Creek fault (an expected result that agreed with the observed ground breakage on the fault during the May 1980 earthquake sequence) and, more surprisingly, an upward bulge of an additional 13 cm across the resurgent dome within the caldera! Although the exact timing of formation of this bulge is not well constrained, horizontal deformation in a broader area to the east (Savage and others, 1981) suggests that it could have formed during the year prior to the major May 1980 earthquake sequence, perhaps coincident with the lesser magnitude quakes occurring along the south margin of the caldera at that time.

Consideration of the sequencial occurrence of the pre-May 1980 seismicity and the four magnitude 6 quakes of May 25-27, 1980 supports the interpretation of Savage and Clark that uplift of the resurgent dome, probably caused by influx of new magma into the subjacent Long Valley magma chamber, triggered the May 1980 Mammoth Lakes earthquake sequence. Rise of magma beneath the caldera may well have caused opening of the south moat ring fractures (signalled by the pre-May 1980 quakes along the south margin of the caldera). Continued uplift eventually may have caused the first and second magnitude 6 quakes of May 25, 1980 on the caldera ring fracture (1 and 2, Figure 4), which in turn released strain on the Sierran frontal fault system, triggering the third and fourth magnitude 6 quakes farther south in the Sierras (3 and 4, Figure 4). Whether rise of magma in the Long Valley chamber was due to internal dynamics or processes affecting its boyancy, or to space accommodated by regional aseismic crustal extension, is an unanswered question that has important bearing on the potential for future volcanic as well as seismic hazards in the area.

In any case, several kinds of evidence -- surface fracturing, ground uplift, seismicity patterns, and major geophysical anomalies -- point to the conclusion that a partially molten magma body lies beneath Long Valley caldera. Furthermore, it is moving and apparently capable of triggering both seismic and possibly future volcanic activity.

COSO VOLCANIC FIELD

The Coso volcanic field, located 200 km south of Long Valley at the southern end of the Owens Valley Rift, is in a tectonic setting similar to that of the Long Valley-Mono Lake field -- that is, in the extensional regime of the east front of the Sierra Nevada. The field has been studied recently by Duffield and Bacon (1979, 1980) under the USGS Geothermal Research Program. They recognize two episodes of volcanism. During the oldest, spanning a 1.5 million-year period from 4 to 2.5 m.y. ago, a heterogeneous and diversified accumulation of basalts, andesites and rhyodacites erupted. The younger episode produced a bimodal group of rhyolite domes and basalt flows which are less than 1.1 m.y. old. The most recent rhyolite eruption was about 44,000 years ago, and the youngest basalt eruption was about 39,000 years ago.

Bacon (1982), using age and volumetric data, derived time-predictive diagrams from which eruption rates and the possible time of future eruptions can be estimated. These diagrams suggest that a rhyolite eruption is not likely at Coso for another 60,000 years, but that basalt could erupt within 1,000 years.

Teleseismic P-wave studies (Reasenberg and others, 1980) indicate that a low-velocity body, interpreted as a magma

chamber, underlies the Coso field at depths of 5 to 20 km. A question, perhaps presently only of academic interest, is whether or not the Coso field, which has evolved to a stage similar to that of the Mono Craters, will eventually evolve to a caldera-forming stage like that of Long Valley. Certain similarities in structural setting and lava chemistry suggest that it could, but the answer will have to await time and the work of future generations of geologists.

CLEAR LAKE VOLCANIC FIELD

The Clear Lake field, in the California Coast Ranges about 130 km north of San Francisco, is in a tectonic setting quite different from that of the Long Valley-Mono Lake and Coso fields. This field lies within the broad right-lateral shear zone of the San Andreas strike-slip system, which may account for some of the differences between the Clear Lake and the other two fields, which are in dominantly tensional tectonic regimes.

The volcanism of the area has most recently been studied by Hearn and others (1976, 1981) and Donnelley-Nolan and others (1981), also under the USGS Geothermal Research Program. The field is the youngest and the northernmost of a chain of progressively older fields that occur to the south. Volcanism began about 2.1 m.y. ago and continued episodically until 10,000 years ago. Four episodes of activity, separated by quiescent periods of about 200,000 years duration, are recognized. The main periods are: 1) 2.1 to 1.3 m.y.; 2) 1.1 to 0.8 m.y.; 3) 0.6 to 0.3 m.y.; and 4) 130,000 to 10,000 years. The general locus of the individual episodes has migrated progressively northward with time. During the first three episodes, the lavas evolved from dominantly basaltic through andesitic to dacitic and rhyolitic, the latter culminating in the voluminous lava outpouring that built Mounts Hanna and Konocti south of Clear Lake. The most recent episode has reverted to dominantly basaltic compositions and is centered further northeast around the eastern shores of Clear Lake.

Gravity (Chapman, 1966, 1975; Isherwood, 1976, 1981) and teleseismic studies (Iyer and others, 1981) suggest the presence at depth of a large magma chamber centered beneath Mount Hannah. However, in the more rhyolitic lavas the absence of chemical characteristics typical of precaldera sequences elsewhere suggests that catastrophic caldera-forming eruptions are less likely here than in the Mono Craters and Coso volcanic fields.

In the most recent, dominantly basaltic episode, centered northeast of the inferred magma chamber, eruptions averaged one every 2,500 years between 130,000 and 10,000 years ago. Whether the past 10,000-year quiescence is just a brief lull within the episode or the beginning of a quiescent period of perhaps 200,000 years is difficult to determine. However, past eruptive episodes have persisted at least 300,000 years, which would suggest the continuation of another 200,000 years of eruptions before another major period of quiescence.

The foregoing summaries and suggested models provide an imperfect and incomplete basis for assessing possible future eruptions and hazards in areas where large magma chambers are known to exist. The emphasis placed on catastrophic caldera-forming eruptions is not intended to imply a need for exceptional concern for such large but infrequent eruptions, but the magnitude of such eruptions is so great and their consequences so disastrous that it is prudent that we study their magmatic systems in as much detail as possible, so that the precursors of such eruptions might be known and recognized in time to provide adequate warnings.

DISCUSSION

Question: You said that the eruptive rate during the last episode at Clear Lake was one eruption every 2,500 years. Yet the most recent eruption was 10,000 years ago. Please explain.

Bailey: Between 130,000 and 10,000 years ago, there were eruptions every 2,500 years. During the past 10,000 years there has been a lull, and this makes it difficult to

project what kind of activity might follow. One can interpret the cessation of activity as the termination of an episode or as a temporary lull within a longer episode, like those that have occurred many hundreds of thousands of years before. We have no way of acquiring the necessary information to predict with any certainty what is likely to follow. At Mono Craters, where eruptions are more frequent and much more reliably dated, we can say with a little more certainty when future eruptions are likely to occur.

Question: What's your feeling about the structure of the Mono Basin?

Bailey: The Mono Craters are within a sag, bounded by concentric normal faults much like the concentric systems that have developed in the vicinity of other calderas, like the Valles (caldera) in New Mexico. Sagging may be produced at the crest of a dome by stretching or extension of the crust, as above an upward bulging magma chamber. Apical sagging is a common response to structural uplift or magma injection, and is akin to the linear graben faults that Robert Christiansen mentioned in the Tennant area near Mount Shasta, where collapse was possibly caused by injection of basaltic magma.

Question: Early geophysical studies did not advocate a magma chamber at the Mono Craters. What is the current thought of geophysicists?

Bailey: There is a small gravity low in the vicinity of Mono Craters depression, but it is not of sufficient size to suggest that it reflects a shallow subcrustal magma chamber. As yet, no other geophysical studies have been done to resolve the problem.

Question: What's your feeling for the relative production rate of magma in each of the three areas discussed, i.e., per unit of time, which area has produced the most material?

Bailey: The total volume of the Coso and Clear Lake volcanic fields is comparable. Each produced about 35 km^3. Although both fields were active over somewhat different times, the Coso beginning 4.0 m.y. ago and the Clear Lake about 2 m.y ago, the total duration of active periods in both fields is about the same, 2 m.y. -- so their relative production rates are comparable. It is more difficult to assess the pre-caldera production rate at Long Valley, because the pre-caldera lavas are significantly modified by erosion. However, the total volume of Long Valley volcanics exceeds 600 km^3, nearly 10 times the combined total of the other two fields; so its production rate over the total 3.5 m.y. active period greatly exceeds that of the others.

Question: Why were the large magnitude 6 earthquakes outside the caldera rather than inside, if you think it's due to some kind of magmatic activity at depth?

Bailey: The Sierran Frontal fault system is probably under continual tensional stress. Magmatic uplift may simply have been the mechanism which released the local strain produced by this stress. Initial upward movement of magma within the caldera may explain why the foreshocks were within the caldera rather than outside. Then, once the strain within the caldera was released, the main frontal fault slipped -- so that the big earthquakes followed on the main tectonic fault. Magmatic uplift was simply the release mechanism.

Question: How deep is this magma beneath the Mono Craters-Long Valley area? If it started to move to the surface, how long would it take to reach the surface?

Bailey: Geophysical evidence suggests that the top of the Long Valley magma chamber may be as shallow as 8 kilometers. However, there is some uncertainty in that figure. How long it would take for the magma to reach the surface would depend upon how fast it moved. That might depend on the kind of mechanisms and processes

going on in the chamber -- which we know little about.

Question: How do you place the three volcanic fields you talked about into a plate tectonics concept?

Bailey: Coso and L Valley both lie on the eastern front of the Sierra Nevada, in a more or less tensional regime (although there is a component of right-lateral strike-slip motion evident in the area). The Clear Lake field lies well within the San Andreas system where right-lateral shear is the dominant stress. Plate tectonics simply provides a model: spreading at the Juan de Fuca Ridge causes the Pacific plate to move westward and the Juan de Fuca plate to move eastward.

The Pacific plate in central California abuts the North American plate along the San Andreas Rift; any acceleration of spreading on the Juan de Fuca Ridge is transmitted through the Pacific plate to the North American plate, which in turn may relieve tensional stress in the Basin and Range. So perhaps the coincidence of the eruption at Mount St. Helens and the earthquakes at Mammoth can be related through plate tectonics in a conceptual way. The fact that the quakes and eruption happened on the very same day is probably fortuitous, but that they happened close together in time may be significant. There has been a general increase in volcanic activity in the Cascades in the last five years and an increase in seismic activity along the Sierra Frontal fault as well. That's the kind of general evidence that suggests there's at least a temporal connection.

REFERENCES

Bacon, C.R., and Duffield, W.A., 1980, Distribution of Quaternary rhyolite domes of the Coso Range, California: implications for extent of the geothermal anomaly: Journal of Geophysical Research, v. 85, p. 2425-2433.

Bacon, C.R., 1982, Time-predictable bimodal volcanism in the Coso Range, California: Geology, v. 10, p. 65-69.

Bailey, R.A., 1980, Structural and petrologic evolution of the Long Valley, Mono Craters, and Mono Lake volcanic complexes, Eastern California (abstract): EOS, v. 61, n. 46, p. 1149.

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, p. 725-744.

Chapman, R.H., 1966, Gravity map of the Geysers area, California: California Division of Mines and Geology, Mineral Information Service, v. 19, p. 178-179.

Chapman, R.H., 1975, Geophysical study of the Clear Lake Region, California: California Division of Mines and Geology Special Report 116, 23 p.

Cramer, C.H., and Toppozada, T.R., 1980, A seismological study of the May 1980 and earlier earthquake activity near Mammoth Lakes, California: California Division of Mines and Geology Special Report 150, p. 91-136.

Curry, R.R., 1971, Glacial and Pleistocene history of the Mammoth Lakes Sierra, California: University of Montana Geological Survey Publications, v. 11, p. 1-49.

Donnelly-Nolan, J.M., Hearn, B.C., Jr., Curtis, G.H., and Drake, R.E., 1981, Geochronology and evolution of the Clear Lake volcanics, U.S. Geological Survey Professional Paper 1141, p. 47-60.

Duffield, W.A., Bacon, C.R., and Dalrymple, G.B., 1980, Late Cenozoic volcanism, structure, and geochronology of the Coso Range, Inyo County, California: Journal of Geophysical Research, v. 85, p. 2381-2404.

Hearn, B.C., Jr., Donnelly-Nolan, J.M., and Goff, F.E., 1981, The Clear Lake

Volcanics: Tectonic setting and magma sources: U.S. Geological Survey Professional Paper 1141, p. 250-45.

Hill, Davis P., 1976, Structure of Long Valley caldera, California, from a seismic refraction experiment: Journal of Geophysical Research, v. 81, p. 745-753.

Isherwood, W.F., 1981, Geophysical overview of the Geysers: U. S. Geological Survey Professional Paper 1141, p. 83-95.

Iyer, H.M., Oppenheimer, D.H., Hitchcock, Tim, Roloff, J.N., and Coakley, J.M., 1981, Large teleseismic P-wave delays in the Geysers-Clear Lake Geothermal area: U.S. Geological Survey Professional Paper 1141, p. 97-116.

Kane, Martin F., Mabey, Don R., and Brace, Rosa-Lee, 1976, A gravity and magnetic investigation of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v.81, p. 754-762.

Kistler, R.W., 1966b, Structure and metamorphism in the Mono Craters quadrangle, Sierra Nevada, California: U.S. Geological Survey Bulletin 1221-E, 52 p.

Lajoie, K.R., 1968, Late Quaternary stratigraphy and geologic history of Mono Basin, eastern California: University of California, Berkeley, Ph.D. thesis, 271 p.

Putnam, W.C., 1949, Quaternary geology of the June Lake District, California: Geological Society of America Bulletin, v. 60, p. 1281-1302.

Reasenberg, P., Ellsworth, W., and Walter, A., 1980, Teleseismic evidence for a low-velocity body under the Coso Geothermal area: Journal of Geophysical Research, v. 85, p. 2471-2483.

Steeples, Don W., and Iyer, H.M., 1976, Low-velocity zone under Long Valley as determined from teleseismic events: Journal of Geophysical Research, v. 81, p. 849-860.

Wood, Spencer, 1977, Chronology of Late Pleistocene and Holocene volcanics, Long Valley and Mono Basin geothermal areas, eastern California: Final technical report, U.S. Geological Survey Geothermal Research Program Contract no. 14-08-0001-15166, 55 p.

CHRONOLOGY OF ERUPTIONS IN CALIFORNIA DURING THE LAST 2,000 YEARS

Richard T. Kilbourne, Geologist
California Division of Mines and Geology
San Francisco, California

ABSTRACT

The length of time since the latest eruption, along with the periodicity and temporal pattern of eruptions, is a useful tool in assessing the risk of future volcanic events. Using occurrence of an eruption in the latest 2,000 years as the definition for active volcanoes, California has at least 27 active vents with 93 dated ash- or lava-producing eruptions. Ten of these vents are in the Cascades; three are in the Mojave Desert; and the remaining 14 are in the Mono Basin-Long Valley region.

Chronological data suggest that a peak eruptive period occurred in both the Cascades and Mono Basin provinces near the year A.D. 900 (+100). Smaller peaks of activity are apparent in the Cascades for the years A.D. 100 (+100) and A.D. 1750 (+100). On a scale of centuries, the eruption-frequency pattern in California seems to follow a Poisson distribution. This pattern suggests that future volcanism would occur as a major period of eruption, lasting perhaps more than a century, followed by centuries of decreasing activity until the next cycle is started. More data are needed before any periodicity for this cycle can be established.

Dating methods most useful in this study are: dendrochronology, historic observation, Carbon-14, rate of formation of obsidian hydration rinds, stratigraphic tephrochronology, and declination magnetostratigraphy. Other methods deserving wider application for dating youthful volcanic events include: lichenometry, palynology, tephrochronology, amino-acid racemination, thermoluminescence, and electron spin resonance. Utilization of these dating methods will undoubtedly add to the list of active volcanoes.

INTRODUCTION

The primary aim of this study was to compile California's age-dated volcanic eruptions -- that is, gather age-dates -- to obtain a picture of eruption frequency and eruption patterns in California. The time period of interest was the latest 2,000 years.

Definition of Active. In looking at the latest 2,000 years of volcanic activity in California, we are seeing the truly "active" volcanoes. The term "active" is more of a lay than a scientific term, but it behooves us to use it when we speak of volcanic hazards because it is one for which the public already has a general understanding. This conference has shown that communication is essential for scientists to properly serve the public in predicting hazards.

The term "active volcano" has been defined in a recent edition of the American Geological Institute Glossary (1980) as: "A volcano that is erupting, also, one that is not now erupting but is expected to do so. There is no precise distinction between an active and a dormant volcano." This definition is imprecise and, as stated, and can be confused with dormant volcano, which has been defined as: "A volcano that is not now erupting but that has done so

within historic time and is considered likely to do so in the future."

The author feels there is a need for a revision of the definition of the term "active volcano." As used in this article, and as I would propose its standardization (Kilbourne and Anderson, 1981): An active volcano is one that is now erupting or one that is known to have erupted within the past 2,000 years. The term "potentially active volcano" is proposed to replace the term "dormant" and to represent a volcano that has erupted in the past two million years but that is not known to have erupted in the last 2,000 years.

These definitions have the advantage of being precise, mutually exclusive, and not overburdened with loosely defined concepts such as "historic time" and "considered likely to erupt in the future."

Uses of Age-Dating in Volcanology. The usefulness of chronological studies of volcanic eruptions lies primarily in volcanic eruption prediction. Simply stated as a modified converse of Hutton's principle of uniformitarianism: The past is a key to the future. Probably nine of ten of the world's eruptions this century were from volcanoes that have previously erupted within the past 2,000 years. It is also reasonable to estimate that 99 of 100 volcanic eruptions this century were from volcanoes that have erupted in the last two million years. Age-dating of the products of eruption identifies these active and potentially active volcanoes.

Age-dating can also be used to discriminate between volcanoes that erupt often from those that erupt seldom. The identification of Mount St. Helens as the most active of the Cascade volcanoes (Crandell and Mullineaux, 1978) was based primarily on age-dating and led to their forecast that Mount St. Helens was likely to erupt before the end of the century.

Another use of age-dating in volcanology is to distinguish patterns of eruptions. When a volcano erupts, does this mean it will be followed closely by further eruptions? larger eruptions? smaller eruptions? eruptions of other volcanoes? When we have answers to these questions, they are usually from the chronological records of its previous eruptive history.

Just as confirmation of the theories of continental drift and the astronomical theories of glaciation has been advanced with age-dating, so too may age dating someday enable us to recognize a periodicity to volcanic eruptions. This would be a major breakthrough in the science of volcanic predictions.

Dating methods found to be most useful in this compilation and listed in order of estimated reliability are: dendrochronology, historic observation, Carbon-14, rate of formation of obsidian hydration rinds, stratigraphic tephrochronology, and declination magnetostratigraphy. Other methods such as lichenometry, palynology, amino-acid racemization, thermoluminescence, and electron spin resonance have the potential to date young volcanic eruptions but have not been used to date any of the specific eruptions compiled in this study. Volcanic events dated only by K-Ar methods or by their general youthful appearance were not added to the list. The margin of error in these methods is considered too great to accurately date events of the past 2,000 years.

Correction Factors. Authors using various dating methods commonly use different notations of age ("years ago," 1776, B.P., etc.). For this study, all dates have been adjusted to calendar years A.D. Uncertainties, if expressed in the original date, have been transferred to the A.D. date. Due to lapses in communication between this author and an original source of a particular date, a correction factor may have been incorrectly applied. The original date source has been quoted verbatim so that any such error(s) could be adjusted in the future.

Radiocarbon dates have consistently involved the most "correction," so the methods used will be detailed here. Before changing to calendar years, C-14 dates were first standardized to B.P. (before 1950) notation and the Libby half-life (5568 years). Ages were then corrected for the atmospheric variation with time of C-14

levels according to the curves of Seuss (1970, 1979) and Stuiver (1978). This last mentioned step adjusts the dates to A.D. calendar years and recorrects for the presently accepted half-life of C-14 (5730 years). At this point, a few radiocarbon dates on wood were further adjusted for the annual rings to the outside ring (presumed year of death).

Source of Error. Not all eruptions of the past 2,000 years are datable nor, in some cases, even identified by geologic study. Lava flows and ash falls in active volcanic regions must bury and obscure earlier flows and ash falls. It is a reasonable estimate that perhaps 40 to 50 percent of the major tephra eruptions during the first millennium have been recognized, dated, and included in the count presented in this paper. For the second millennium, we recognize perhaps 75 percent of the major events. These are estimates only.

Another problem in deciphering a complete volcanic history is that of erosion and varied wind distribution of tephra. Because of the easy erodability of unconsolidated volcanic materials, and the lack of detailed study of such deposits on a statewide basis, it is logical to assume that the count of eruptions presented in this paper represents mainly major eruptions. The list of dated eruptions in California is certainly incomplete and includes only larger eruptions that have left substantial ash or lava deposits in locations that are well exposed or that have been subject to detailed tephrostratigraphic study.

RESULTS

Tabulation of Eruptions. Table 1 is a compilation of California's dated eruptions less than 2,000 years old. It shows that we have had at least 93 volcanic eruptions from some 27 active vents over the past two millennia. For the purpose of counting eruptions, each clearly distinguishable volcanic rock unit is considered a separate eruption. The locations of prominent young volcanoes or vent areas are shown in Figure 1.

California is not a single volcanic province. Study of temporal patterns of volcanism is most productive through the study of individual tectonic regions. California's Cascade Range is such a region. A histogram of dated volcanic eruptions for the Cascades (see Christiansen, 1982, this volume) is presented in Figure 2. This histogram suggests three periods of relatively high volcanic activity in the Cascade in the past 2,000 years. It also suggests a Poisson distribution for eruptive events with major periods of activity followed by centuries of decreasing activity. It may be significant that, at least in the most recent two periods of high volcanic activity (800-1000 A.D. and 1600-1800 A.D.), all three of California's major Cascade volcanoes, Mt. Shasta, Lassen Peak, and Medicine Lake Highlands, erupted.

In the Mono Basin-Long Valley region, the Poisson distribution of eruptions (Figure 3) is even more evident, with only one peak period of eruptive activity between 800-1000 A.D.

The histogram of Figure 4 shows the frequency of eruptions, based upon the data from Table 1, for the entire State of California. Table 2 summarizes some statistical conclusions to be drawn from the regional and statewide eruption frequencies. The average number of eruptions over the centuries, projected into the future, serves to alert us that the hazard should not be ignored in emergency planning. The statistical data is preliminary at this stage but stresses the importance of gathering more geotechnical data useful for specific time and place predictions.

In further study of recent regional volcanism in California, if a pattern emerges that can be correlated with a causative force or even one that simply establishes a predictable periodicity to eruptions, a significant reduction in volcanic risk would be attained. With this objective, the California Division of Mines and Geology would appreciate receiving any new data on the age-dating of recent California eruptions.

ACTIVE VOLCANIC REGIONS OF CALIFORNIA

For the purpose of a comparative discussion, California can be divided into five active volcanic regions: Shasta, Lassen Peak, Medicine Lake Highlands, Mono Basin-Long Valley, and Mojave Desert (Figure 1).

The Shasta region contains only one documented active volcano, Hotlum Cone or Mt. Shasta itself. The record of the last 2,000 years shows this large strato-volcano to be capable of destructive explosive eruptions.

The most recent eruption occurred in 1786. There are no good local eyewitness accounts, but the eruption was large enough to be seen by Captain La Perouse while sailing off the northern California coast (Finch, 1930). Miller (1980) describes and documents pyroclastic flows and hot mudflows that appear to be associated with this most recent activity.

In planning for the next destructive eruption of Mount Shasta, it is consistent with the recent geologic record to expect a moderate to large explosive event similar in type to the most recent eruptions of Mount St. Helens. Shasta is larger than either and is presumably capable of large eruptions. It is also reasonable to assume that such an event would occur within the next 200-300 years.

The rare case of a Mt. Mazama or Mt. Tehama caldera-forming type eruption (Christianson, 1982, this volume), though possible because of Shasta's great size, seems too remote to warrant planning at this stage. This caldera-producing type of event has been documented as happening only once (Mount Mazama eruption about 7,000 B.P.) in the last 10,000 years for the whole Cascade chain.

The Lassen Peak region contains at least three volcanoes documented as active. They are: Lassen Peak (last eruption 1914-1921), Cinder Cone (last eruption 1850-1851), and a dome near Chaos Crags (last eruption 1854-1857). All of these and most of the earlier eruptions from the Lassen Peak region have been relatively small eruptions, affecting areas which are now mostly included in Lassen Peak Volcanic National Park.

Lassen Peak and its two associated volcanoes probably represent the most active region in California. Though most historic eruptions have been small, Lassen, like its similar sized and active neighbor to the north, Mount St. Helens, is believed capable of much larger eruptions. A repeat eruption in this region could be expected within the next 100 years, but further study and geophysical monitoring is needed before a forecast can be made.

Medicine Lake Highlands is one of the least known of California's volcanic regions. More than 100 cinder cones, domes, and lava flows are found in this region; most of the vents are parasitic to or superimposed on a large shield volcano. At least four vents (Table 1) are classified as active (dated as erupting in the last 2,000 years). These include Glass Mountain, Little Glass Mountian, High Hole Crater, and Cinder Butte. Heiken (1978) suggests that its main volcanic center lies at the intersection of several normal faults. As would be expected in a shield volcanic, most of the eruptive products are lava rather than pyroclastic.

The earliest eruptions were mostly of fluid basaltic lava whereas the most recent eruptions were rhyolitic. This distinction is important in assessing volcanic hazards because rhyolitic magma tends to erupt more explosively, producing ash and pumice. However, these recent rhyolitic eruptions in the Medicine Lake Highlands have been small and relatively nonexplosive.

The most recent eruption in this area occurred at Glass Mountain in the spring of 1910 (Finch, 1928). It was a very minor eruption which, if it had not been witnessed, would probably not be listed in Table 1.

An earlier and larger 1750 event was a fissure eruption producing a rhyolitic lava flow and eight lava domes. Interestingly, this 1750 eruption is believed to be recorded in local Indian myths (Kilbourne and Anderson, 1981), and has been dated by Carbon-14 and obsidian hydration rind methods.

CALIFORNIA'S ACTIVE VOLCANOES

DATED AS ERUPTING WITHIN THE LAST TWO THOUSAND YEARS

Figure 1

Table 1

CALIFORNIA'S ACTIVE* ERUPTIVE VENTS

(Compilation by R. Kilbourne, November 1, 1981)

ESTIMATED ERUPTION DATE (A.D.)**	LOCATION	TYPE OF ERUPTION(S)	DATING METHOD, UNCORRECTED C-14 DATES AND REFERENCES
1914-1921	Lassen Peak, main dome	Steam and ash explosions, mudflows trusion of lava dome	Historic documentation (Loomis, 1926; Day and Allen, 1925)
1910	Glass Mountain, Medicine Lake Highlands	Minor ash eruption	Historic documentation (Finch, 1928)
1890?	Beneath southern part of Mono Lake	Sublacustral phreatic explosion	Historic documentation (Townley and Allen, 1939; and Kilbourne and others, 1980)
1854-1857	From dome near Chaos Crags north of Lassen Peak	Phreatic steam and gas	Historic documentation (Brewer, 1930)
1850-1851	Cinder Cone near Lassen Peak	Basalt lava flow and tephra	Historic documentation (Harkness, 1875)
1750-1855	Paoha Island in Mono Lake	Dacite tephra cones (several) and dacite lava flow	Age estimated by young geomorphic expression and lack of shoreline features in 1885 (Russell, 1889); area was inhabitied since about 1855
1786	Mount Shasta	Steam and ash eruption, pyroclastic flow, hot mudflows	Historic observation (Finch, 1930; Miller, 1980)
1785	Cinder Cone near Lassen Peak	Basalt lava flow	Dendrochronology (Finch, 1937; James, 1966)
1750	Glass Mountain, Medicine Lake Highlands	Lava flow and domes (at least 8) along fissure type eruption with viscous rhyolitic lava	Obsidian hydration rind date calculated from rind thickness of 1.3 ± 0.2 microns (Friedman, 1968), assuming initial rind of 0.5 microns is formed in first 20 years, and later rind forms at same rate as Panum Crater (Wood and Brooks, 1979); historic observation from Modoc Indian legend (Powers, 1932); Wintu Indian myth (Kilbourne and Anderson, 1981); C-14 dates by Friedman (1968)
1720	Cinder Cone near Lassen Peak	Basalt lava flow forming Snag Lake	Dendrochronology (Finch, 1937; James, 1966)
1650(?)-1690	Chaos Jumbles avalanches from Chaos Crags north of Lassen Peak	Three separate volcanic debris avalanches	Dendrochonology, botanical succession, soil develoment, and lichenography (Heath, 1960; Crandell and others, 1974)
1667±200	High Hole Crater at Burnt Lava flow, Medicine Lake Highlands	Lava flow	C-14 200, 200, 220, 320, all ± 200 BP (Ives and others, 1964)
1666	Cinder Cone near Lassen Peak	Basalt tephra and lava flow	Dendrochronology (Finch, 1937; James, 1966)
1645±?	Mono Craters	Phreatic explosion of probably pre-existing volcanic debris	C-14, 250 BP (Bailey, 1981, oral communication)
1500 or 1650±?	Youngest dome in Cima volcanic field	Basalt lava flow and dome	C-14, "330-480 years old" this date already includes Seuss (1980) corrections (Katz and Boettcher, 1980)
1240-1855	Negit Island on Mono Lake	Rhyodacite lava flows	Overlies tephra unit on Negit Island dated 1240 A.D.; and habitation of area since 1855 (Wood, 1977b; Kilbourne and others, 1980)
1567	Cinder Cone near Lassen Peak	Basalt lava flow	Dendrochronology (Finch, 1937; James, 1966)
1480±200	Cratered dome of Mono Crater chain	Rhyolite dome	Obsidian hydration rind thickness (Wood, 1977b; Kilbourne and others, 1980)
1410±200	North side of Mammoth Mountain	Phreatic explosion	C-14, 500 BP ± 200 (Bailey and Koeppen, personal communication to Wood, 1977b)
1400±60	Southernmost Inyo Crater	Phreatic explosion	C-14, 710 ± 60 (Wood, 1977a)
1310±40	Panum Crater, Mono Craters	Pumice tephra explosion and dome formation	C-14, 680 ± 40 BP (Wood and Brooks, 1979)

Table 1 (continued)

1260±?	Hotlum Cone, Mount Shasta	Pyroclastic debris flow	C-14, "about 700 years ago" (Miller, 1980)
1245±60	South Oeadman Creek dome-Inyo Craters	Pumice lapilli and ash eruption, dome formation	C-14, 760 ± 60 BP, 725 ± 60 BP (Wood, 1977a, Tephra 1)
1215±?	Hotlum Cone, Mount Shasta	Hot mudflow	C-14, "about 750 years ago" (Miller, 1981)
1150±200	Paoha Island, Mono Lake	Sublacustral dome	Obsidian hydration rind thickness (Wood, 1977b; Kilbourne and others, 1980)
Between 1245±60 and 800±65	North and South Oeadman Creek domes-Inyo Craters	10 airfall ash layers, five of which appear equivalent to 10 ash layers in nearby section, total of 15 eruptions	Stratigraphically enclosed by C-14 dated Tephra 1 and Tephra 2 (Wood, 1977a, 1977b)
1000±200	Oome on NW edge of NW Coulee-Mono Craters	Tephra explosion and dome formation	Obsidian hydration rind thickness and regional stratigraphy relative to other dated units (Wood, 1977b; Kilbourne and others, 1980)
980±300	Chaos Crags, West bank of Lost Creek NNE of Lassen Peak	Oldest of 4 pyroclastic flows exposed along West bank of Lost Creek	C-14, 1010 ± 250 BP (Crandell and others, 1974); see also C-14 dates, 1000 ± 300 and 1000 ± 300 (Spiker and others, 1977); these other dates are from the Lost Creek area and could represent a major regional eruption about 980-990 A.O.
910±90	Little Glass Mountain-Medicine Lake Highlands	Pumice tephra deposit followed by lava flow and dome	C-14, 1065 ± 90 BP (Heiken, 1978)
890±?	Hotlum Cone, Mount Shasta	Pyroclastic flow	C-14, "about 1,100 years ago" (Miller, 1980)
850±300	Chaos Crags, Manzanita Creek deposits	3rd oldest of 4 pyroclastic flows in Manzanita Creek	Underlain by dated (800 A.O. ± 28) flow, overlain by two younger flows with trees older than 325 years (in 1974); younger two units could possibly correlate with Lost Creek Valley section. Original C-14 date 1120 ± 300 BP (Crandell and others, 1974)
840±60	Callahan flow from Cinder Butte	Lava flow and probable tephra	C-14, 1110 ± 60(Oonnelly, pers. comm., 1981); declination magnetostratigraphy (O. Champion, pers. comm.198
800±65	Panum Crater, Mono Basin	Plinean eruption and dome	C-14, 1175 ± 65 BP and 1210 ± 65 BP (Wood, 1977a)
800±300	Chaos Crags, Manzanita Creek deposits, NNE of Lassen Peak	Oldest of 4 pyroclastic flows in Manzanita Creek	C-14 dates from Manzanita Creek on presumably same deposit; original dates 1200 ± 300 and 1230 ± 300 BP (Spiker and others, 1977; Crandell and others, 1974)
660±240	Near Glass Mountain, Medicine Lake Highlands	Pumice tephra deposits	C-14, 1360 ± 240 BP (Chesterman, 1955)
500±300	Northwest part of Northwest Coulee-Mono Craters	Explosive tephra eruption rhyolitic obsidian flow	Obsidian hydration rind thickness and stratigraphy relative to other dated units (Wood, 1977b; Kilbourne and others, 1980)
480±200	South Coulee(?)-Mono Craters	Pumice tephra eruption	C-14, 1520 ± 200 BP (Wood, 1977b)
300±200 or 330±200	South Coulee(?)-Mono Craters	Pumice tephra eruption	C-14, 1695 ± 200 BP (Wood, 1977b)
230±?, or 180±?, or 120±?	Hotlum Cone (?), Mount Shasta	Several pyroclastic flows	C-14, "About 1,800 years ago" (Miller, 1980)
75±300	Northwest (?) Coulee, Mono Craters	Obsidian flow	Obsidian hydration rind thickness and stratigraphy relative to other dated units (Wood, 1977b; Kilbourne and others, 1980)
230 A.O. 170 B.C.	Hotlum Cone (?), Mount Shasta	Andesite lava flows	Stratigraphically bounded by C-14 dated units, dated as "about 1,800 and about 2,1000 years ago (Miller, 1980)
10 A.O. ± 200	South Coulee (?), Mono Craters	Pumice tephra eruption	C-14, 1990 ± 200 (R. Buckman, personal communication to S. Wood, 1976, see Wood, 1977b)

* Active volcano defined as a vent that has erupted within the latest 2,000-year period (Kilbourne and Anderson, 1981).

** Eruption dates derived from C-14 dates have been corrected for secular variations in atmospheric C-14 according to the curves of Seuss (1970, 1980) and Stuiver (1978). C-14 dates on trees have been corrected for annual rings to the outside of the tree (actual date of death). If more than one plausible date results, all are listed. BP = Years Before 1950 A.D.

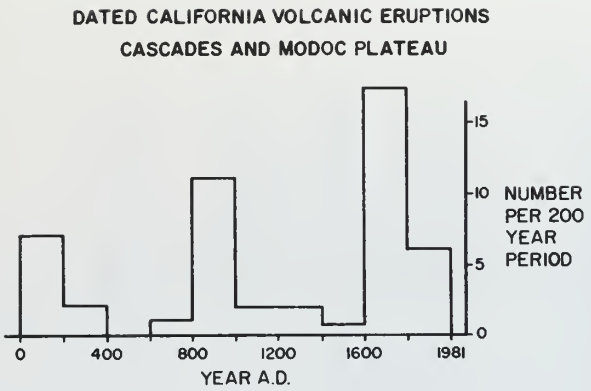


Figure 2

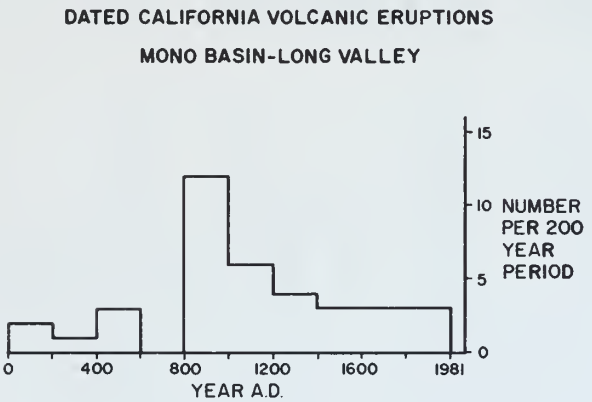


Figure 3

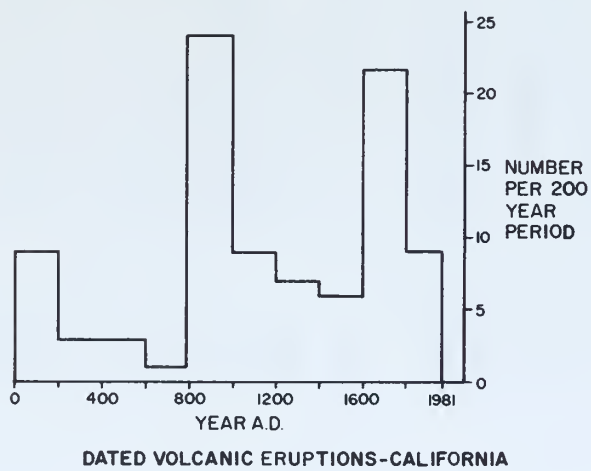


Figure 4

Table 2. Simple statistical predictions - volcanic eruptions in California for the next century.

Region	Pattern	Eruptions/Century		
		Actual Average dated eruptions past 2000 years	Factored Average past 2000 years*	Visual Extrapolation of frequency histogram of next century
Mono	Poisson	1.85	2.77	1.5
Cascades	Poisson	2.55	3.77	1.75
All California	Poisson?	4.4	5.54	3.3

* Assuming eruptive frequency has been progressively obscurred, the following factors (multipliers) were used to compensate for this presumed loss of data: 0-200 A.D. x 2.5; 200-400 A.D. x 2.25; 400-600 A.D. x 2.0; 600-800 A.D. x 1.75; 800-1000 A. D. x 1.5; 1000-1200 A.D. x 1.45; 1200-1400 A.D. x 1.35; 1400-1600 A.D. x 1.25; 1600-1800 A.D. x 1.15; and 1800-1981 x 1.0.

Based on the chronology and types of past eruptions, future activity in the Medicine Lake Highlands might be small eruptions of ash and pumice tephra, perhaps a lava flow or cinder cone, but probably not explosive or far-reaching in their impact. Glass Mountain, a historically active site, and the seismically active area around the town of Tennant and Stephens Pass would appear to be likely sites for future eruptions in the regions as suggested by Christiansen (1982, this volume).

The Mono Basin-Long Valley region, which has recently been the site of unusual earthquake activity and seismic swarms (Sherburne, 1980), contains a chain of more than a dozen active craters and domes. At least 30 eruptions have been dated as occurring in the last 1,981 years (Wood, 1977; Kilbourne and others, 1980). The latest eruption was a minor phreatic explosion occurring in 1890. It is documented only by a single newspaper report describing the unique phenomena that would be associated with a sublacustral (Mono Lake) volcanic explosion.

The Mono Basin-Long Valley region was first studied in detail by Russell (1889). It has long been recognized as an area of recent volcanism and spectacularly scenic volcanic landforms. Most of the domes and coulees (viscous lava flows with blocky, steep-fronted form) are rhyolitic. This region is quite removed from the plate boundary tectonics of the Cascade Range and is one of two active intracontinental volcanic vent areas in the United States (San Francisco volcanoes in Arizona being the other).

The mechanism for eruption (Kilbourne and others, 1980) in this region may include large earthquakes and earthquake swarms that open fractures through which lava begins rising to the surface. Such swarms have been associated with other rhyolitic volcanoes (Minakami, 1974). The author agrees with Bailey's (1982, this volume) recent assessment that this region has a high potential for eruption within the next 50 years.

The Mojave Desert appears to be the least active of the five named volcanic regions. The youngest dome in the Cima volcanic field is the only vent presently documented as active (last eruption about 1500 or 1650, see Table 1 and Katz and Boettcher, 1980). The region as a whole contains several young basaltic lava flows and cinder cones of undetermined age. As with earlier eruptions, future activity is likely to be outpourings of lava and construction of cinder cones -- not a particularly hazardous type of eruption in a sparsely populated area.

(DISCUSSION follows the Christiansen paper.)

REFERENCES

American Geological Institute (AGI), 1980, Glossary of Geology, 805 p.

Bailey, R.A., 1982, The Long Valley-Mono, Coso, and Clear Lake volcanic fields, in this volume.

Brewer, W.H., 1930, Up and down in California: Yale University Press, p.458-66.

Chesterman, C.W., 1955, Age of the obsidian flow at Glass Mountain, Siskiyou County, California: American Journal of Science, v. 253, p. 418-424.

Christiansen, R.L., 1982, Volcanic hazards in the California Cascades: Mt. Shasta, Medicine Lake Highland, and Lassen Park, in this volume.

Crandell, D.R., Mullineaux, D.R., Sigafoos, R.S., and Rubin, M., 1974, Chaos Crags eruptions and rockfall-avalances, Lassen Volcanic National Park, California: Journal of Research of the U.S. Geological Survey, v. 2, n. 1, p. 49-60.

Crandell, D.R., and Mullineaux, D.R., 1978, Potential hazards from future eruptions of Mt. St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

Day, A.L., and Allen, E.T., 1925, The volcanic activity and hot springs of Lassen Peak (California): Carnegie Institute Washington Publication 360, 190 p.

Finch, R.H., 1928, Lassen Report No. 14: The Volcano Letter, n. 161, p. 1.

Finch, R.H., 1930, Activity of a California volcano in 1786: The Volcano Letter, n. 308, p. 1.

Finch, R.H., 1937, A tree ring calendar for dating volcanic events, Cinder Cone, Lassen National Park, California: American Journal of Science, v. 33, p. 140-146.

Friedman, I., 1968, Hydration rind dated rhyolite flows: Science, v. 159, February 23, p. 878-880.

Harkness, H.W., 1875, A Recent Volcano in Plumas County: Proceedings of the California Academy of Sciences, v. V, p. 409-412.

Heath, J.P., 1960, Repeated avalanches at Chaos Jumbles, Lassen Volcanic National Park: American Journal of Science, v. 258, n. 10, p. 744-751.

Heiken, G., 1978, Plinian-type eruptions in the Medicine Lake Highlands, California, and the nature of the underlying magma: Journal of Volcanology and Geothermal Research, v. 4, p. 375-402.

Ives, P.C., Levin, B., Robinson, R.D., Rubin, M., 1964, U.S. Geological Survey Radiocarbon Dates VII: Radiocarbon, v. 6, p. 37-76.

James, D.E., 1966, Geology and rock magnetism of Cinder Cone lava flows, Lassen Volcanic National Park, California: Geological Society of America Bulletin, v. 77, p. 303-312.

Katz, M., and Boettcher, A., 1980, The Cima Volcanic Field, in Fife, D.L., and Brown, A.R., editors, Geology and mineral wealth of the California Desert: South Coast Geological Society, p. 236-241.

Kilbourne, R.T., Chesterman, C.W., and Wood, S.H., 1980, Recent volcanism in the Mono Basin-Long Valley region of Mono County, California, in Sherburne, R.W., editor, 1980, Mammoth Lakes, California earthquakes of May 1980: California Division of Mines and Geology, Special Report 150, p. 7-22.

Kilbourne, R.T., and Anderson, C.A., 1981, Volcanic history and "active" volcanism in California: California Geology, v. 34, n. 8, p. 159-168.

Loomis, B.F., 1926, Pictorial history of Lassen volcano, 108 p.

Malone, S., 1982, The Mount St. Helens Eruptions: Seismic monitoring for eruption prediction, in this volume.

Miller, C.D., 1980, Potential hazards from future eruptions in the vicinity of Mount Shasta volcano, northern California: U.S. Geological Survey Bulletin 1503, 1980.

Powers, Howard A., 1932, The lavas of the Modoc Lava Bed quadrangle, California: The American Mineralogist, v. 17, n. 7, p. 253-284.

Russell, C., 1889, Quaternary history of Mono Valley, California: U.S. Geological Survey, Eighth Annual Report, Part 1, p. 1-495.

Seuss, H.E., 1970, Radiocarbon Variation and Absolute Chronology: Proceedings of the 12th Nobel Symposium, Olsson, editor, Stockholm, Almquist and Wiksell, p. 595-605.

Seuss, H.E., 1979, A calibration table for conventional radiocarbon dates, in Proceedings of the Ninth International Conference on Radiocarbon Dating, Los Angeles and La Jolla, p. 777-784.

Stuives, M., 1978, Radiocarbon timescale tested against magnetic and other dating methods: Nature, v. 273, p. 271-274.

Townley, S.D., and Allen, M.W., 1939, Descriptive catalog of earthquakes of the Pacific Coast of the United States, 1769 to 1928: Bulletin of the Seismological Society of America, v. 29, no. 1, p. 1-297.

Wood, S.H., 1977a, Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo craters, eastern

California: Geological Society of America Bulletin, v. 88, p. 89-95.

Wood, Spencer H., 1977b, Chronology of late Pleistocene and Holocene volcanics, Long Valley and Mono Basin geothermal areas, eastern California: Final Technical Report, March 1977, sponsored by the U.S. Geological Survey, Contract no. 14-08-0001-15166, 77 p.

Wood, S.H., and Brooks, R., 1979, Panum Crater dated 640-40 years, B.P., Mono Craters, California: Geological Society of America, Abstract with Programs, v. 11, no. 7, p. 543.

VOLCANIC HAZARD POTENTIAL IN THE CALIFORNIA CASCADES

Robert L. Christiansen
U.S. Geological Survey, Menlo Park, California

ABSTRACT

The Cascade Range, which extends 200 km into northern California, includes three long-lived compound volcanoes or volcanic systems capable of eruption. Eruptions should also be expected from other, short-lived volcanoes in the Cascade Range.

Mount Shasta, the most voluminous andesite-dacite stratovolcano of the Cascades, has been constructed, primarily in four major cone-building episodes, since about 450,000 years. B.P. During the past 10 000 years, it has erupted at least once every 600-800 years. Many of the eruptions produced debris flows, and some produced pyroclastic flows. Although Mount Shasta has not erupted voluminous lavas or pumice in about the past 2,000 years, small eruptions have continued to within the past 200 years. Eruptions that could be expected in the future range from small events high on the cone that would have little surrounding effect to pyroclastic eruptions that could produce destructive ash flows. Such a large, long-lived stratovolcano that has been through several thousand years of relative quiescence could even produce a catastrophic caldera-forming pyroclastic eruption, although nothing specific in Mount Shasta's recent history indicates that it is evolving toward such an eruption.

The Medicine Lake volcano, a broad shield with a shallow caldera, may have evolved for more than a million years. Most of the exposed shield-forming lavas, some as young as Holocene, are andesite or basalt. Two ash-flow eruptions have produced tuff sheets with volumes of several cubic kilometers: a silicic tuff on the order of one million years old is exposed to the north, and a widely exposed upper Pleistocene andesitic tuff was erupted from the summit area. Holocene eruptions, some as recent as 1,000 years B.P., produced either basalt or rhyolite to dacite and affected mainly the shield itself. Almost all Holocene lavas high on the shield are silicic; low on the flanks, only mafic lavas have erupted. This distribution suggests that a large silicic magma chamber could exist beneath the central area of the volcano. Such a chamber might be capable of producing voluminous ash flows and caldera subsidence.

Lassen Peak is one of a cluster of dacitic domes and flows formed within the past 250,000 years on the northeast flank of a deeply eroded 500,000-year-old stratocone. Lassen Peak itself is a large 11,000-year-old dome; the adjacent Chaos Crags domes were emplaced only about 1,100 years B.P. There are more than a dozen other domes, flows, and related fallout deposits, some of which are associated with pumiceous ash flows. The 1914-1915 eruptions began with steam-blast eruptions near the summit of Lassen Peak but later produced minor dacitic lava and pumice; the most vigorous eruptions produced mudflows that extended more than 30 km down the valley of Hat Creek. The historic eruptions and the numerous young dacitic centers, considered together with the active hydrothermal systems of the region and active seismicity, indicate an active silicic magma body. The possible locations of vents for future silicic, possibly explosive, eruptions anywhere in the dacitic field make this potentially one of the most dangerous volcanic areas of the Cascades.

Besides these three major volcanic systems, there are many smaller edifices,

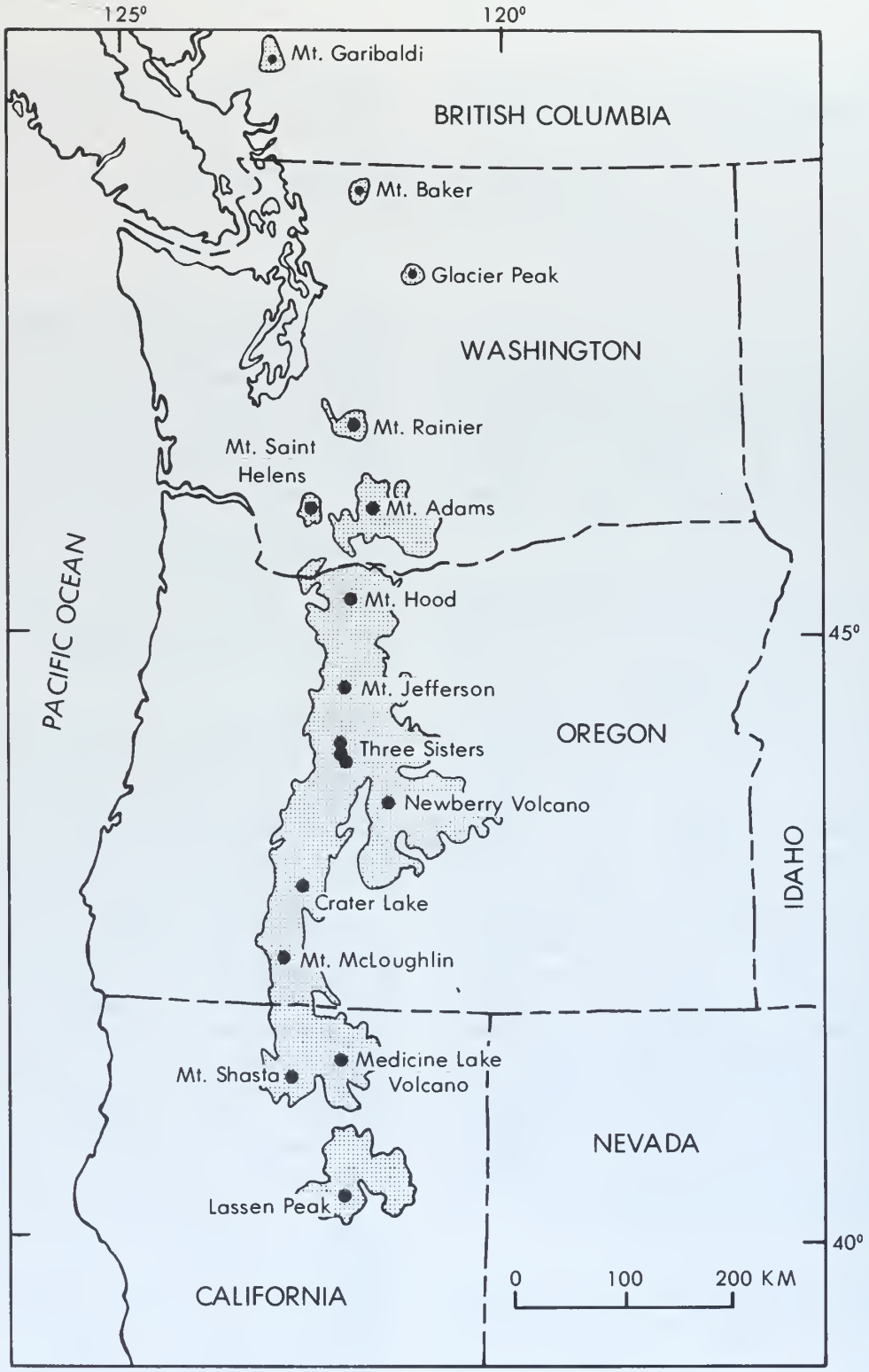


Figure 1. Index map showing Pliocene and Quaternary volcanic rocks of Cascade Range.

from small shields to single-eruption cinder-and-lava fields. The latest eruption of one of these smaller volcanoes was in 1850-1851 at Cinder Cone in Lassen Volcanic National Park. Similar future eruptions should be expected; their sites probably would not be known long in advance and are more likely to be at new vents than at existing ones. Swarm seismicity like that of recent years near Stephens Pass and Tennant could precede such a mafic eruption.

INTRODUCTION

The Cascade Range includes a generally north-trending chain of Quaternary volcanoes that extends from northern California through Oregon and Washington into southern British Columbia (Figure 1). In the northernmost part of the range, Quaternary volcanic activity generally has been isolated and centered around a few large stratovolcanoes. From southern Washington southward, cover by Quaternary volcanic rocks becomes more continuous and vents more abundant, especially through most of Oregon. In California, the Quaternary volcanic products are less continuous than in Oregon, and young volcanoes mostly cluster around major centers.

The southern part of the Cascade volcanic chain extends about 200 km into northern California and is marked by two discrete areas of Pliocene and Quaternary volcanism that contain three major long-lived volcanic systems. The northern area includes Mount Shasta, the Medicine Lake Highland, and numerous small volcanoes between and around the two major centers as well as along a northwest- to north-trending axis of volcanic vents between them. The southern area includes Lassen Peak and closely associated vents, as well as another group of volcanoes along a northwest- trending axis. A topographic map (Figure 2) accentuates these two regions of Quaternary volcanism, which are separated both topographically and geologically. The map (Figure 2) also shows the close topographic relation between Mount Shasta and the Medicine Lake Highland, each of which lies to one side of the Cascade axis. Another conspicuous regional volcanic feature, mainly of Tertiary age, is the Modoc Plateau, which stands at a relatively consistent level east of the Cascade Range, below the Cascades but higher than the Sacramento and Shasta Valleys that lie west of the range.

Volcanic hazards in the Cascades and a rationale for assessment of hazards at specific volcanoes were discussed comprehensively by Crandell and others (1979). In this report, I do not attempt to duplicate that type of analysis, but rather I present a brief overview of Quaternary volcanism in the California Cascades, with emphasis on the kinds of future volcanic activity that might be expected, the possible localities of future eruptions, and the significance of the similarities and differences among the several types of volcanic systems that make up the California Cascades. Such a broad overview cannot take the place of specific hazards assessments at individual volcanoes, such as that for Mount Shasta by Miller (1980) or that now underway for the Lassen Peak area by L.J.P. Muffler and others (1982), but it can provide a perspective and a point of departure for broad considerations of volcanic hazards in this active region.

MOUNT SHASTA

Mount Shasta is the most voluminous Quaternary stratovolcano of the Cascades. It is a typical andesite-dacite composite volcano (Williams, 1934) that may serve as a good model for how such stratocones are built and for some of the types of activity that can be expected from them in the future. It is worth noting that, although Mount Shasta conforms to the commonly held but simplistic image of a volcano, in some senses it might better be termed a "volcanic system." In this report, I use that term for a large volcano that has numerous vents, has evolved complexly over a long time (more than 100,000 years), and has changed its style of activity over time. Defined this way, a volcanic system is the expression of an even larger magmatic system that includes the subvolcanic and plutonic roots of the volcanic system as well as zones of magma generation and related transformations of the crust and upper mantle.

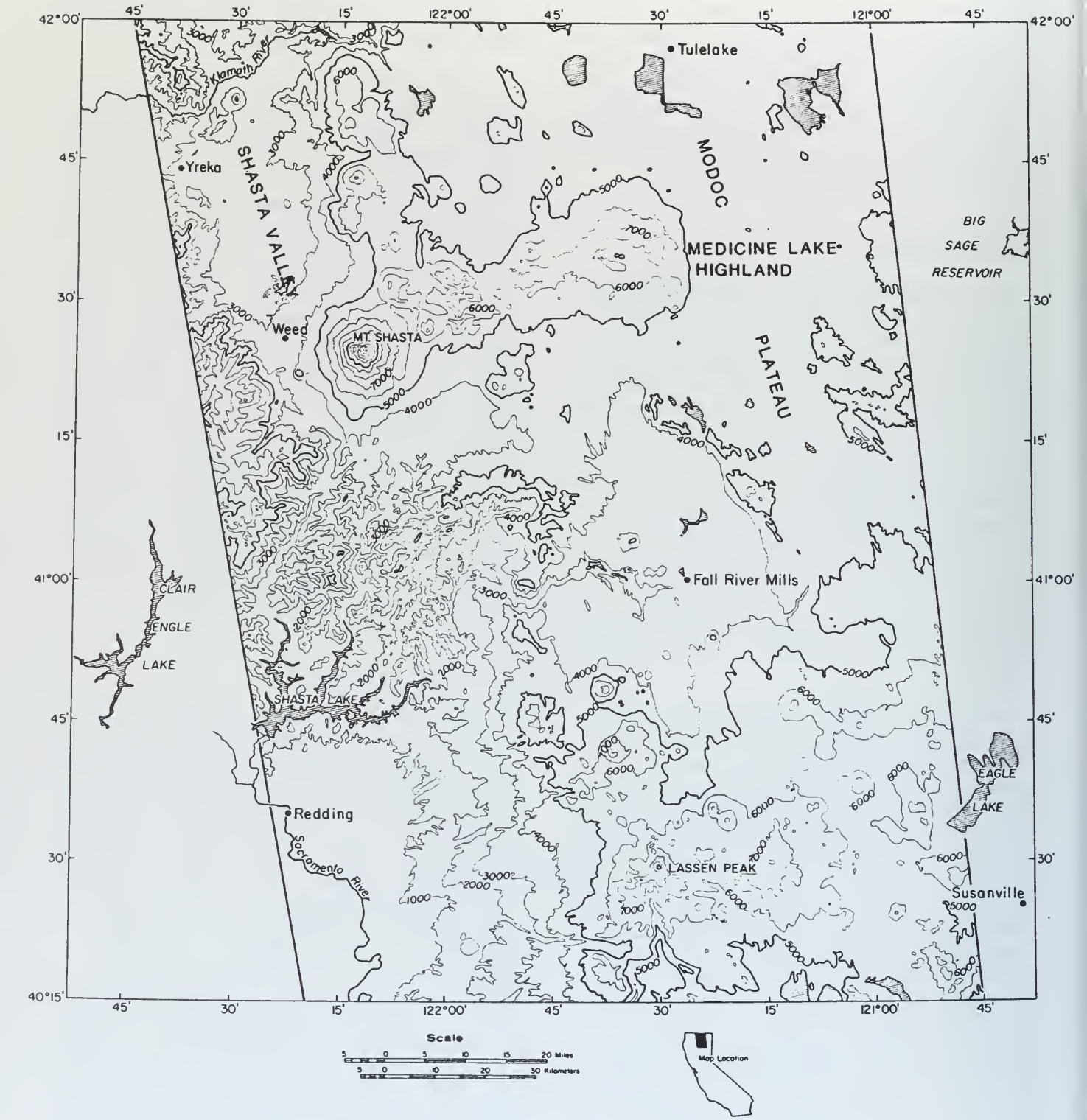


Figure 2. Topographic map of Cascade Range and nearby areas in northern California. Contour interval, 1,000 feet (after R. Couch, Oregon State University, unpublished data, 1981).

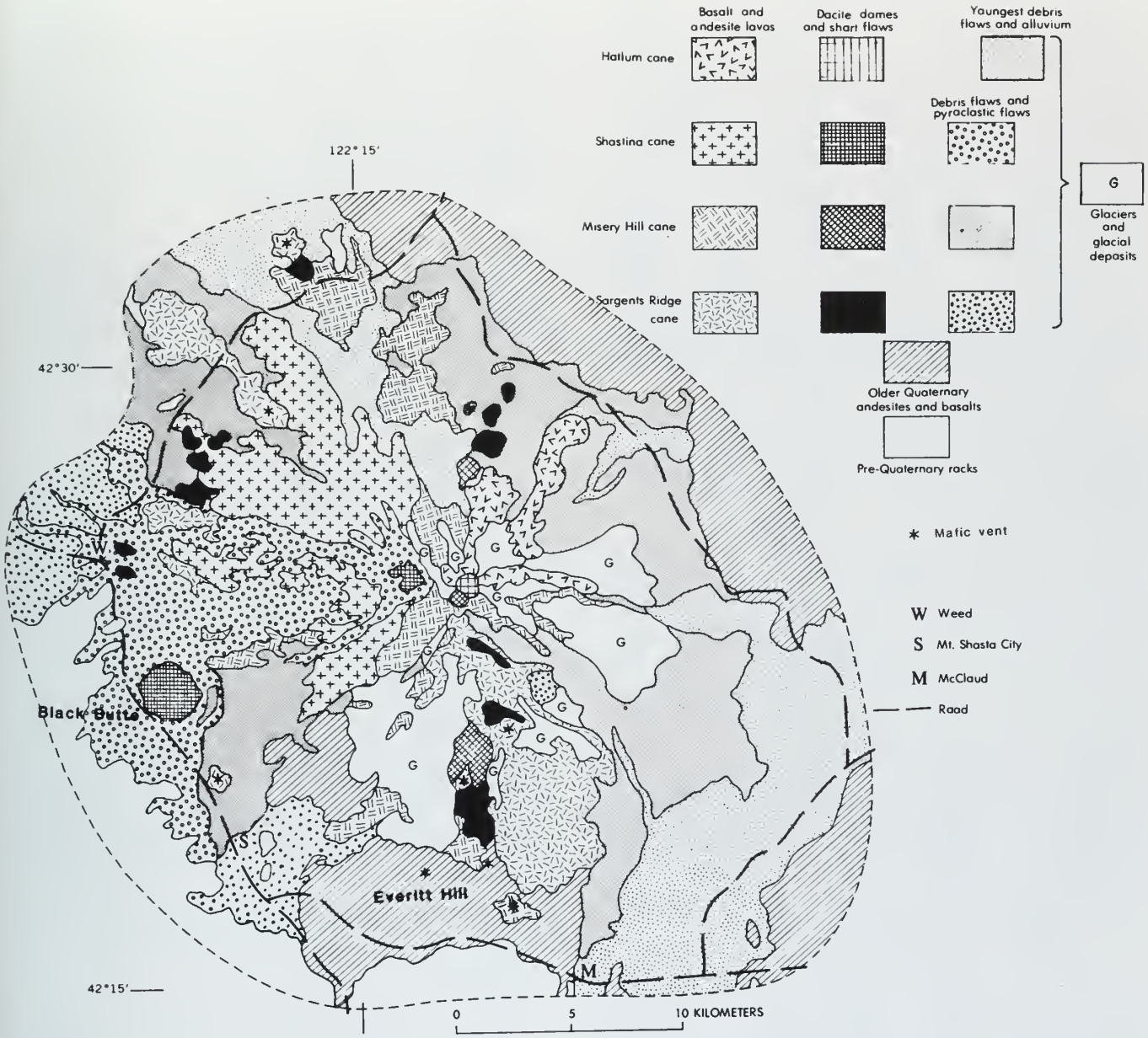


Figure 3. Geologic map of Mount Shasta (after Christiansen and others, 1977).

The Compound Cone

In recent collaborative work (Christiansen and Miller, 1976; Christiansen and others, 1977), we have recognized four major cone-building episodes that have constructed most of the Shasta volcanic edifice. Each of the four cones of Mount Shasta is more or less uniform in chemical and mineralogic composition, and each cone was little eroded during its major growth. Nearly 90 percent of the volume of the stratocone probably consists of two-pyroxene andesitic lavas that were erupted from the four central vents during rather brief episodes -- probably lasting only a few thousand years or less -- separated by relatively longer periods of erosion and more varied but commonly smaller eruptions.

The Sargents Ridge cone, the oldest of the four, grew around a central vent high on the south side of present Mount Shasta (Figure 3). Growth of the cone began sometime after about 450,000 years B.P., as shown by K-Ar dates on the underlying Everitt Hill shield (G.B. Dalrymple, unpublished data, 1979). Relations with older till deposits indicate that the Sargents Ridge cone grew mainly before at least part of a major glaciation of pre-Tioga age. A large area (nearly 350 km^2) of unusual hummocky topography northwest of Mount Shasta appears to be the partly buried deposit of a very large avalanche-landslide that catastrophically disrupted the Sargents Ridge or a predecessor cone in an episode perhaps similar to the May 18, 1980, eruption of Mount St. Helens, Washington (Christiansen and Peterson, 1981).

The Misery Hill cone was formed by lavas that were erupted from just south of the present summit, burying much of the north flank of the Sargents Ridge cone and partly filling deep erosional valleys in it. This cone was built before the major glacial advance during the Tioga glaciation, probably 15,000 or 20,000 years ago, and its summit crater was partly filled by the dacite dome of Misery Hill.

Shastina, a conspicuous peak on the west side of Mount Shasta, stands somewhat apart from the other three cones and would be one of the major stratovolcanoes of the Cascades if it stood by itself. It is the best dated of Shasta's four cones. Shastina overlies the widespread pumice of Red Banks, dated at about 9,700 ^{14}C years (Miller, 1980), and the last eruptions of Shastina produced dacitic domes and pyroclastic flows about 9,400 years B.P. (Miller, 1978). Such short eruptive episodes, of only a few hundred to perhaps a few thousand years, may have been typical of the growth of each of Shasta's four major cones and perhaps of many other Cascade stratocones.

Probably the youngest of the four cones is the Hotlum, which forms the present summit and northeast flank of Mount Shasta (Figure 3). The Hotlum cone is less well dated than Shastina but probably largely postdates it, as shown by its relations to Neoglacial deposits.

In contrast to the four brief episodes of major cone building, intervening periods were relatively long, commonly tens of thousands to hundreds of thousands of years. Erosion was predominant as lavas accumulated slowly. Eruptions during these periods commonly occurred from flank vents, and the compositions of the lavas were more varied than those of the main cones, ranging from basalt to rhyodacite. During each of these periods, dacitic domes were emplaced in the summit crater of the preceding cone and commonly on the flanks as well. The positions of all the flank vents, either within an approximately north-trending broadly arcuate zone through the summit or west of that line, indicates structural control of the volcanism.

Fragmental Deposits

A large proportion of Shasta's eruptions have produced fragmental deposits. As seen in the deep valley of Mud Creek that exposes the Sargents Ridge cone, about half the volume of volcanic materials forming the compound cone consists of fragmental deposits. Many were deposited as debris flows that were mobilized either by the melting of ice and snow during eruptions or by external sources of water in noneruptive processes, such as occurred in climatically

induced mudflows during 1924 and 1977 (Hill and Egenhoff, 1976; Miller, 1980). Some of these debris-flow deposits extend more than 10 km onto and beyond the volcano's lower flanks.

Many eruptions also have produced pyroclastic flows, some of which extended more than 20 km from their vents. These pyroclastic flows are particularly well displayed around Shastina and Black Butte, a dome low on its west flank (Miller, 1978). Most are lithic pyroclastic flows, possibly related to the explosive disruption or collapse and avalanching of hot volcanic domes or lava flows; some pumiceous ash flows also formed during pyroclastic eruptions. Relative to some other large Cascade stratocones, however, a proportionately smaller amount of pumiceous ash has been erupted, and distal fallout deposits are sparse.

Potential Hazards

Miller (1980) considered factors in the evolution of Mount Shasta as well as a detailed analysis of the stratigraphy of its Holocene deposits, to designate several zones of volcanic hazard potential. The zones of greatest risk are around the major central vents; risks decrease radially outward. Beyond the volcano's immediate flanks, the effects of local topography become important in controlling the distribution of far-traveled debris flows and pyroclastic flows.

Mount Shasta has erupted at least once every 600-800 years for the past 10,000 years (Miller, 1980). The last voluminous lava or pumice associated with a major eruption are older than about 2,000 years, but Mount Shasta has produced numerous smaller, more recent eruptions. It erupted at least as recently as about 200 years B.P. and may have been witnessed in eruption from sea by the explorer, LaPerouse, in 1786 (Finch, 1930). A small event is reported to have occurred in 1855 (Eichorn, 1954), but its nature is uncertain.

Expectable future volcanic activity from Mount Shasta could range from small vulcanian eruptions high on the cone, which would have little effect on surrounding areas, to large pyroclastic eruptions that could produce ash flows to 20 km or farther. Because the volcano has evolved complexly over a long time and because each cone-building episode was both preceded and followed by silicic eruptions, the Mount Shasta magmatic system probably has generated a rather large subvolcanic silicic intrusion through the course of its evolution; part of this body may still exist as an eruptible volume beneath the stratocone. From a large, long-lived andesitic to dacitic volcano that has been relatively quiescent for several thousand years, as Mount Shasta has, even a voluminous caldera-forming pyroclastic eruption is within the range of possible behavior. Although no specific data at hand indicate that Mount Shasta is evolving toward a catastrophic eruption like that of Mount Mazama about 6,850 years B.P. (Williams, 1942; Bacon, 1982), such behavior should be considered among Shasta's potential long-term hazards.

MEDICINE LAKE VOLCANO

Whereas Mount Shasta lies just west of the axis of the Cascade Range, the Medicine Lake Highland is east of that axis and nearly symmetrically opposite (Figure 2). The more or less symmetrical positions of these two volcanic systems, as well as a large negative gravity anomaly that includes both of them (LaFehr, 1965), suggest that they are parts of an even larger magmatic system that dominates this part of the Cascades. Despite this possible relation, the Medicine Lake Highland comprises a quite different volcanic system -- a large shield-like edifice with a shallow caldera. The Medicine Lake lavas typically include both more mafic and more silicic types than are common in large stratocones like Mount Shasta. Although no individual long-lived major central vents are obvious on the highland, its flanks are dotted with numerous monogenetic vents. Nevertheless, like Mount Shasta, the Medicine Lake volcano is an edifice built by a closely related long-lived group of eruptive vents that has evolved complexly and systematically (Anderson, 1941; Donnelly-Nolan and others, 1981).

The Volcanic Shield

The highland probably has grown over a period of more than a million years. Most of the exposed lavas that appear to be parts of the shield edifice (Figure 4) range in composition from basalt to andesite; the summit area is also underlain by rhyolite that now occurs only as inclusions in the more mafic lavas. Some of the shield-forming lavas are as young as Holocene. J.M. Donnelly-Nolan (unpublished data, 1982) has shown that two ash-flow sheets with volumes of at least several cubic kilometers erupted from the Medicine Lake volcano. A rhyolitic or dacitic tuff exposed to the north has reverse paleomagnetic polarity (D. Champion, unpublished data, 1982) and, thus, probably is older than about 700,000 years; an andesitic tuff exposed mostly on the flanks of the shield, but also in the caldera, was associated with late Pleistocene summit eruptions.

Holocene eruptions from the Medicine Lake volcano generally have produced either basalt or rhyolite to dacite, and some single eruptive sequences have produced both. On the upper parts of the shield, including the caldera area, the Holocene lavas are generally silicic or are composites that incorporated basaltic magma blebs into rhyolitic magma (Eichelberger, 1975). Low on the north and south flanks, high-alumina basaltic lavas dominate. The most recent eruptions, both basaltic and silicic, occurred about 1,000 or 1,100 years B.P. to form rhyolite to dacite domes and flows near the east and west rims of the caldera -- Glass Mountain and Little Glass Mountain -- and basaltic lavas on the north and south flanks (Heiken, 1978). Fallout deposits of rhyolitic pumice related to these recent eruptions are thick in the vicinity of the caldera.

Potential Hazards

Expectable eruptions from the Medicine Lake volcano are most likely to produce basaltic or mafic-andesitic lavas and cinder cones or rhyolitic to dacitic lavas and fallout deposits. Although they could have significant effects on parts of the highland, even to its lowest flanks, only falls of pumice or ash from such eruptions would be likely to affect areas much beyond the shield itself. The distribution of silicic Holocene lavas on the upper part of the shield, however, and the eruption of only mafic lavas on the flanks suggest that a moderately large silicic intrusion could exist beneath the caldera. If much of this body remains molten, the possibility exists that the volcano could produce a voluminous silicic ash-flow eruption, perhaps associated with caldera subsidence, and the occurrence of two such pre-Holocene eruptions should be considered in hazards analysis.

LASSEN DOME FIELD

Because of its early-20th-century eruptive activity, as well as its local topographic prominence, Lassen Peak has been the focus of attention for possible future volcanic activity in the California Cascades. Lassen Peak itself, however, is only one of a cluster of dacitic domes and flows that has formed during about the past 250,000 years (G.B. Dalrymple, unpublished data, 1982) and that, like Mount Shasta and the Medicine Lake volcanoes, probably should be considered a volcanic system (Figure 5). These domes all lie on the deeply eroded northeast flank of a 500,000-year-old stratocone, called either Mount Tehama or the Brokeoff cone (Williams, 1932; Fountain, 1979). Williams (1932) suggested that a caldera collapse formed the present topographic depression within this old stratocone, but later workers have generally regarded the depression as erosional (Bowen, 1978; Kane, 1980, p. 85; L.J.P. Muffler and M.A. Clynne, unpublished data, 1982).

The Dome Field

Lassen Peak is a very large dacitic dome, formed about 11,000 years B.P. (Crandell, 1972). Most volcanic domes are single-eruption features that formed in a few hours to a few days or complexes of individual eruptive domes and flows that accumulated in rather short eruptive episodes lasting a few decades at most. The eruptions of 1914-1915 -- tailing off with milder eruptions for another two years and vigorous

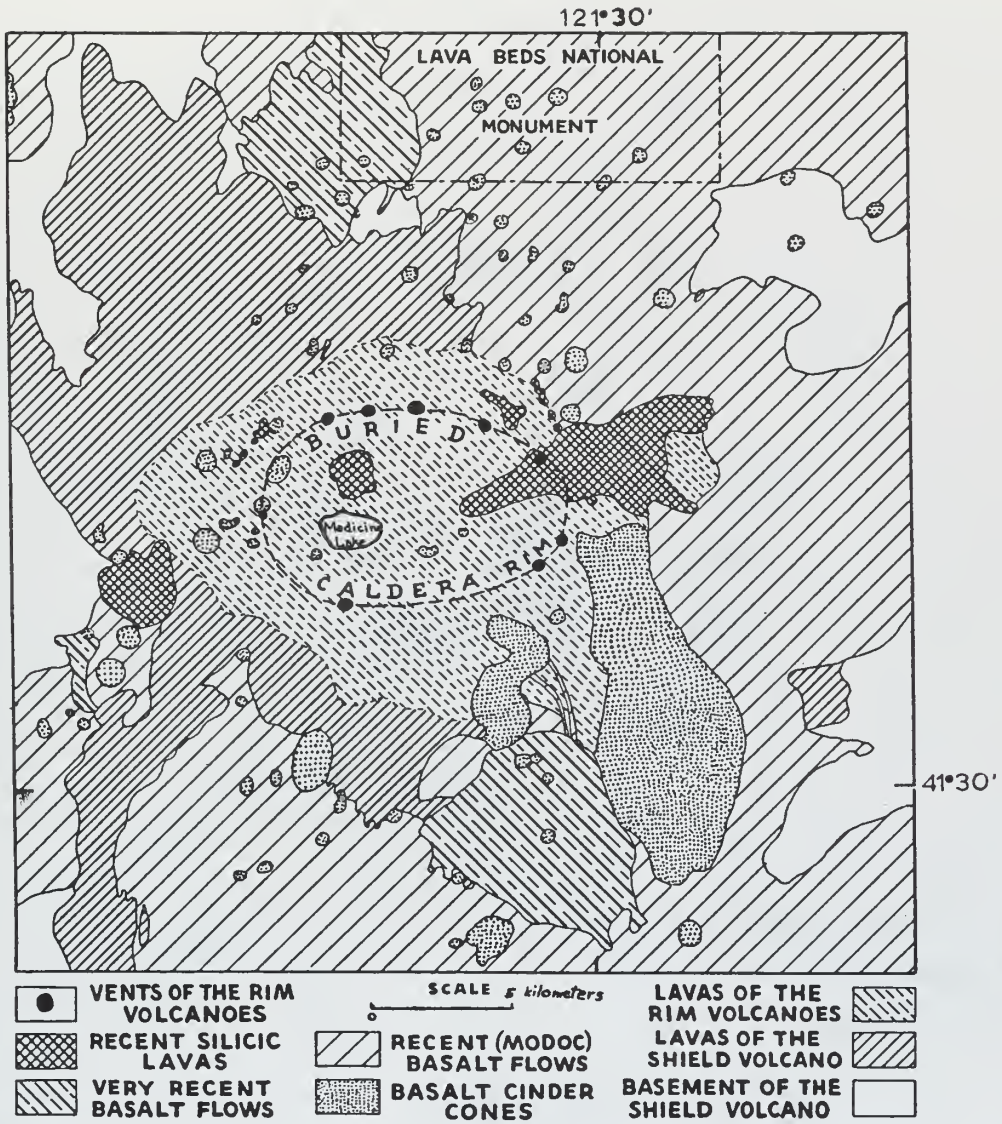


Figure 4. Geologic map of Medicine Lake volcano (after Anderson, 1941).

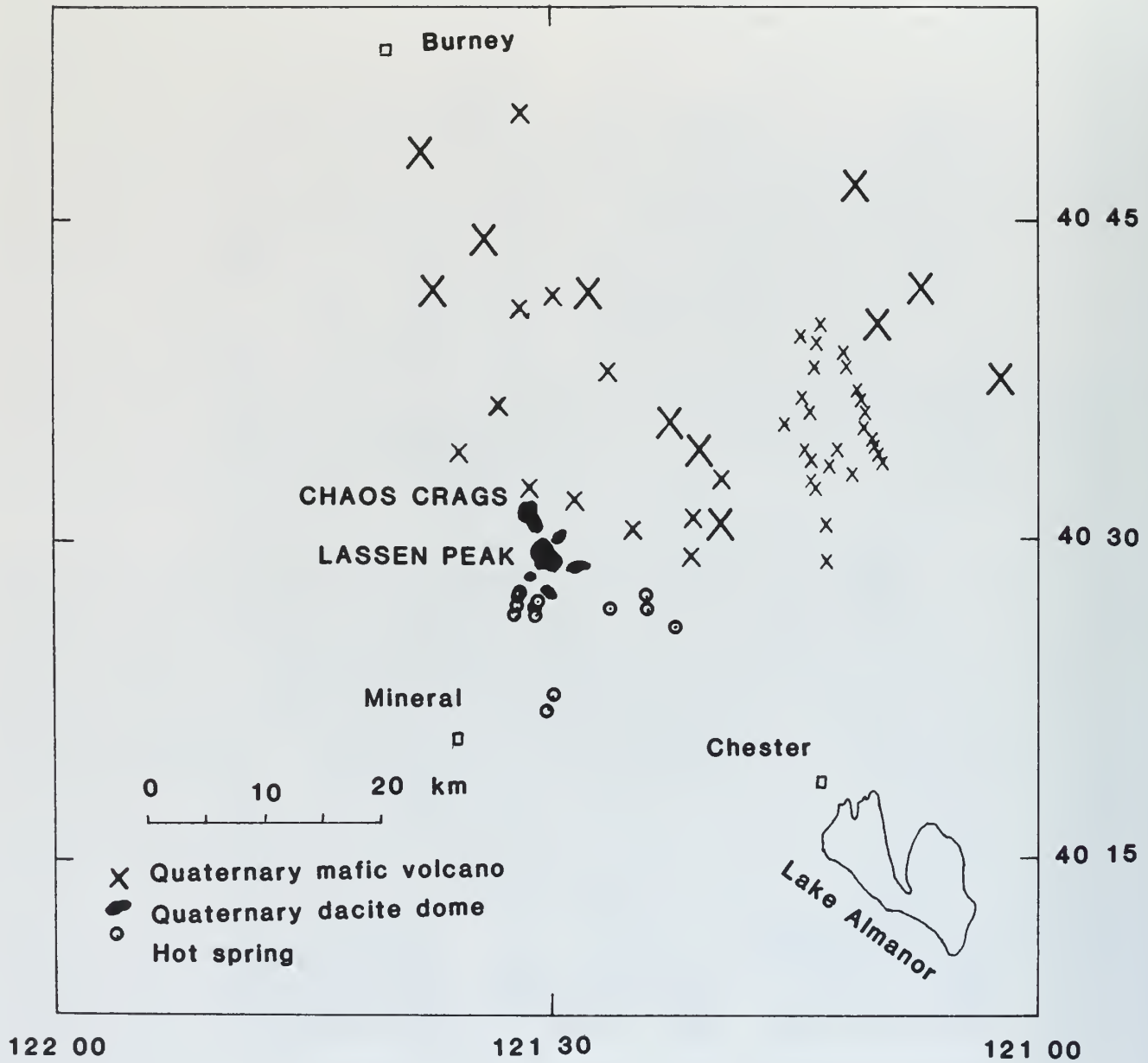


Figure 5. Youngest volcanic and tectonic features of Lassen Peak area (after Lydon and others, 1960; Heiken and Eichelberger, 1980).

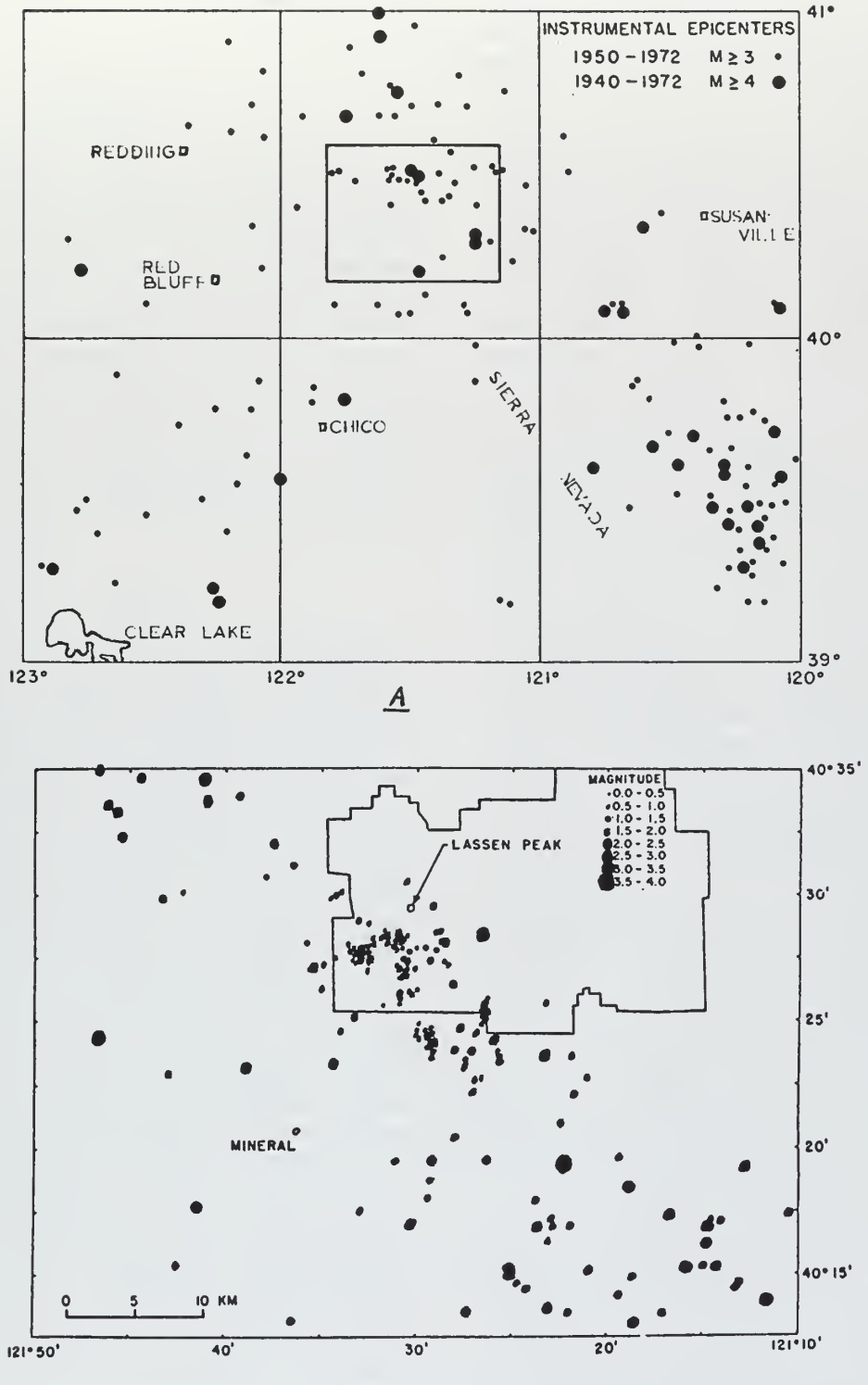


Figure 6. Seismicity of Lassen Peak region. A, Epicenters of earthquakes recorded in 1940-72 of magnitude 3 and larger; rectangle encloses area of fig. 6B. B, Epicenters of earthquakes recorded in January 1977-February 1978 of magnitude 0 and larger; irregular outline encloses area of Lassen Volcanic National Park (after Klein, 1979).

fumarolic and minor explosive activity until about 1921 -- may or may not have been directly related to the magma that formed the dome of Lassen Peak near the end of Pleistocene time.

The 1914-1915 eruptions (Day and Allen, 1925; Loomis, 1926; Finch, 1927) were characterized by a series of explosive blasts from the summit area. The earliest were steam-blast eruptions that formed a small crater near the summit, probably caused by the emplacement of magma into a water-saturated volcanic edifice. A similar mechanism operated during the first two months of eruptive activity in 1980 at Mount St. Helens before its climactic blast and magmatic eruption of May 18 (Christiansen and Peterson, 1981). The most important later eruptions of Lassen Peak, which occurred in May 1915, were associated with the emplacement of a dacitic lava flow and pumiceous ejecta. The most vigorous of these eruptions produced large mudflows down the slopes of the peak. One especially large mudflow down the northeast side of the volcano on May 20 swept more than 30 km down the valley of Hat Creek to the north and was followed two days later by a lateral blast that devastated an area of several square kilometers on the east side of the peak.

Besides the historical eruption from Lassen Peak, the youngest major event in the Lassen dome field was the emplacement of the Chaos Crags domes, probably about 1,100 years B.P. (Crandell and others, 1974; Heiken and Eichelberger, 1980). In addition to the domes, the Chaos Crags eruptions formed pumice cones around the vents and moderately extensive pumiceous pyroclastic flows. It is not known whether a group of devastating rockfall-avalanches that fell from Chaos Crags to produce Chaos Jumbles about 300 years B.P. (Crandell and others, 1974) were associated with renewed eruptive activity. Chaos Crags was reported to be steaming as late as the 1850s, and that steaming might have indicated residual heat from somewhat earlier eruptive activity.

There are more than a dozen older dacitic domes, flows, and related pyroclastic deposits in the Lassen field, some of which were associated with pumiceous ash flows that extended considerably beyond the eruptive vents.

Seismicity

A plot of recent earthquake epicenters in the vicinity of Lassen Peak (Figure 6B) reveals a linear pattern trending northwest through the dome field (Klein, 1979). A regional plot (Figure 6A) appears to show an intersection of seismic zones in the Lassen area: one zone extends northwestward from the frontal fault system of the Sierra Nevada, and the other trends northeast through the vicinity of Chico. The most frequent earthquakes in the region are those that occur as swarms centered in the Lassen volcanic and hydrothermal area.

Potential Hazards

The Lassen dome field is the center of a system of vigorous hydrothermal activity, the hottest part of which is centered on the southwest side of the dome cluster (Muffler and others, 1982). Together, this hydrothermal system, the early-20th-century eruption, the continuing seismicity, and the numerous clustered young dacitic centers (Figure 5) indicate an active silicic magmatic system. This system lies within a large negative gravity anomaly (LaFehr, 1965) somewhat analogous to what encloses both Mount Shasta and the Medicine Lake Highland, and some studies have suggested that this anomaly relates to a plutonic body which might sustain a larger Lassen-region magmatic system (Heiken, 1976; Heiken and Eichelberger, 1980). Future eruptions from the Lassen group of volcanoes would be likely to produce not only dacitic domes or lava flows but also pumiceous fallout deposits and, possibly, voluminous pyroclastic flows. Pumiceous ash flows could devastate areas many tens of kilometers from their eruptive vents. Vents for future eruptions could be not only at Lassen Peak or Chaos Crags but also virtually anywhere within the field of dacitic domes. Consequently, the Lassen dome field should be regarded as one of the principal candidates in the Cascade Range for future silicic, probably explosive eruptions:

potentially, this could be one of the most dangerous volcanic areas of the Cascade Range.

OTHER VOLCANOES

In addition to the three major volcanic systems described above, which command most of the attention for volcanic hazards in the California Cascades, hundreds of smaller volcanic edifices (Figure 7; see Luedke and Smith, 1981) range from small commonly monogenetic shields to cinder-cone/lava-flow fields that formed in single short eruptive episodes (for example, Williams, 1949). These volcanoes generally are basaltic to andesitic. It is important that large areas of past eruptive activity also be considered for their potential volcanic hazards.

Although the localities of future outbreaks of this type of volcano probably could not be determined long in advance, such eruptions should be expected in the future. The latest was that of 1850-1851 (Finch and Anderson, 1930) at Cinder Cone in Lassen Volcanic National Park (Figure 5). Although it is difficult or impossible to forecast where the next eruption from one of these small volcanoes might be, more such eruptions certainly will occur and are probably even more likely to occur through new vents than from existing ones.

Such eruptions might be expected to begin along northwest- to north-trending fissures, subparallel to regional normal-fault trends, and to produce mafic lavas or cinders; if activity were to persist for more than a few hours or days, it would be likely to centralize to form one or a few cinder cones. Persistent swarm-type seismic activity is likely to precede eruptions although seismicity might be recognized as a precursor to volcanic activity only shortly before an eruption -- or, even, only in hindsight.

Earthquake-swarm activity has occurred intermittently in the past few years near Stephens Pass and Tennant, in the area of the Cascade axis about midway between Mount Shasta and the Medicine Lake Highland (Figure 8). In 1978, earthquake swarms were centered in the vicinity of Stephens Pass (Bennett and others, 1979). They were not mainshock and aftershock sequences like those typically associated with tectonic strain release; instead, the earthquakes occurred in swarms similar to those commonly associated with hydrothermal or volcanic activity. The 1978 swarm occurred intermittently over a period of a few months and included several events of magnitude 3 and greater. Activity ceased until January 1981, when another swarm occurred about 10 km north near the town of Tennant. Surface breaks were associated with the 1978 activity, although the earthquake magnitudes were smaller than those that typically produce surface displacements. The breaks consisted of open ground cracks and small discontinuous grabens with no predominant sense of offset, similar to features associated with earthquake swarms along the volcanic rift zones of Kilauea, Hawaii, and the neovolcanic zone of Iceland. One possible, though tentative, explanation for these events near Stephens Pass and Tennant is that they reflected the injection of dikes to high levels in the crust. Although the data at hand do not specifically suggest the likelihood of basaltic eruptions in the area in the near future, an intrusive model can be considered as one possible working hypothesis for the 1978 and 1981 activity.

DISCUSSION, Christiansen and Kilbourne

Question: Is there any indication of seismic swarm activity in the area between Shasta and Medicine Lake in the 50 years or so prior to the 1978 swarm?

Christiansen: We know of no such seismic swarms in that area. However, seismic instrumentation has been very sparse in the region, and it's only been in the last few years that we have had anything like a comprehensive seismic network. Events like this would have been marginally detectable with previously existing seismic nets, and the swarm-like character would probably not have been detectable even if individual events had been recorded. The area has had

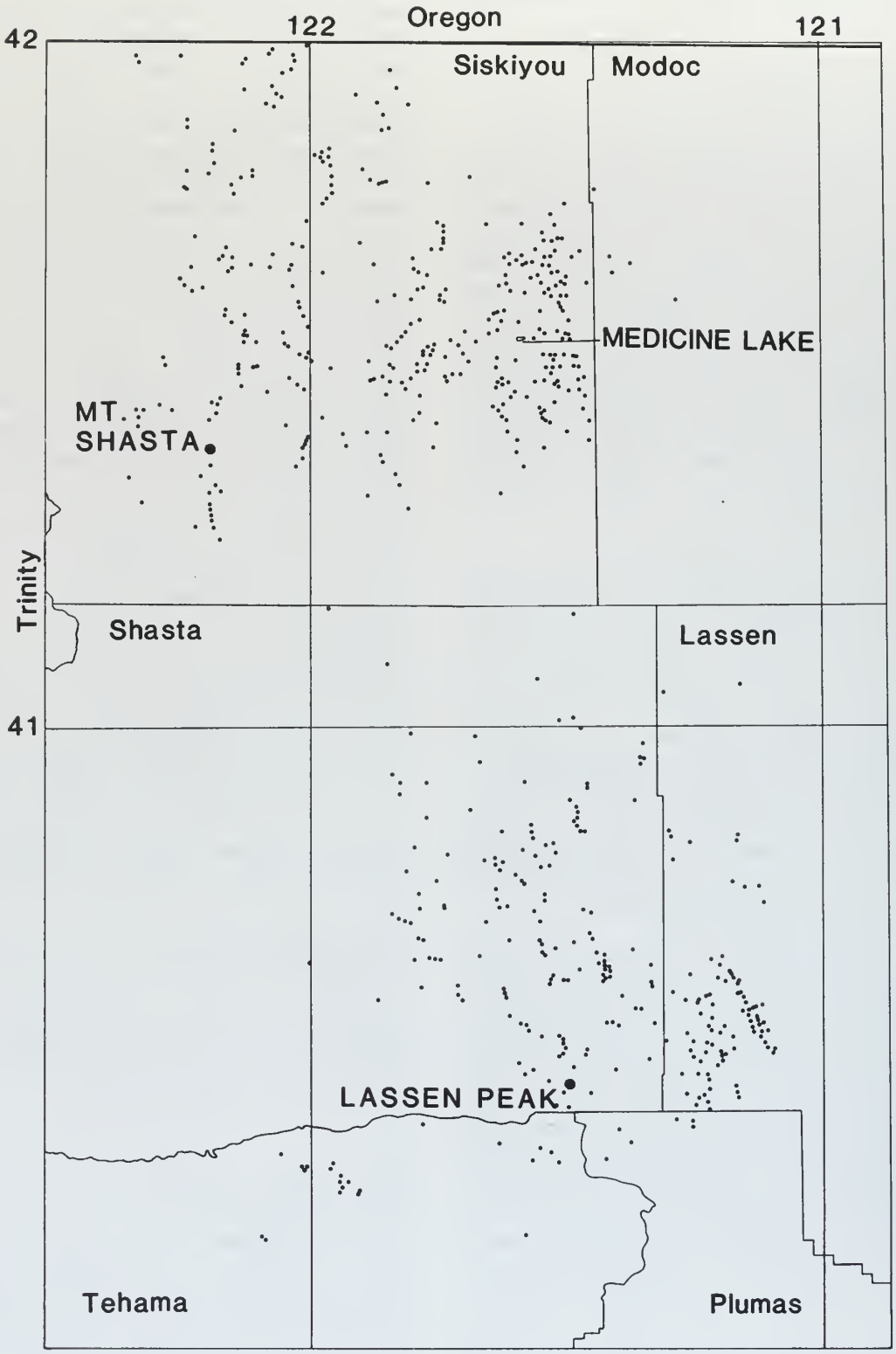


Figure 7. Volcanic vents of Pliocene and Quaternary age in Cascade Range of northern California. County boundaries are shown for reference (after Luedke and Smith, 1981).

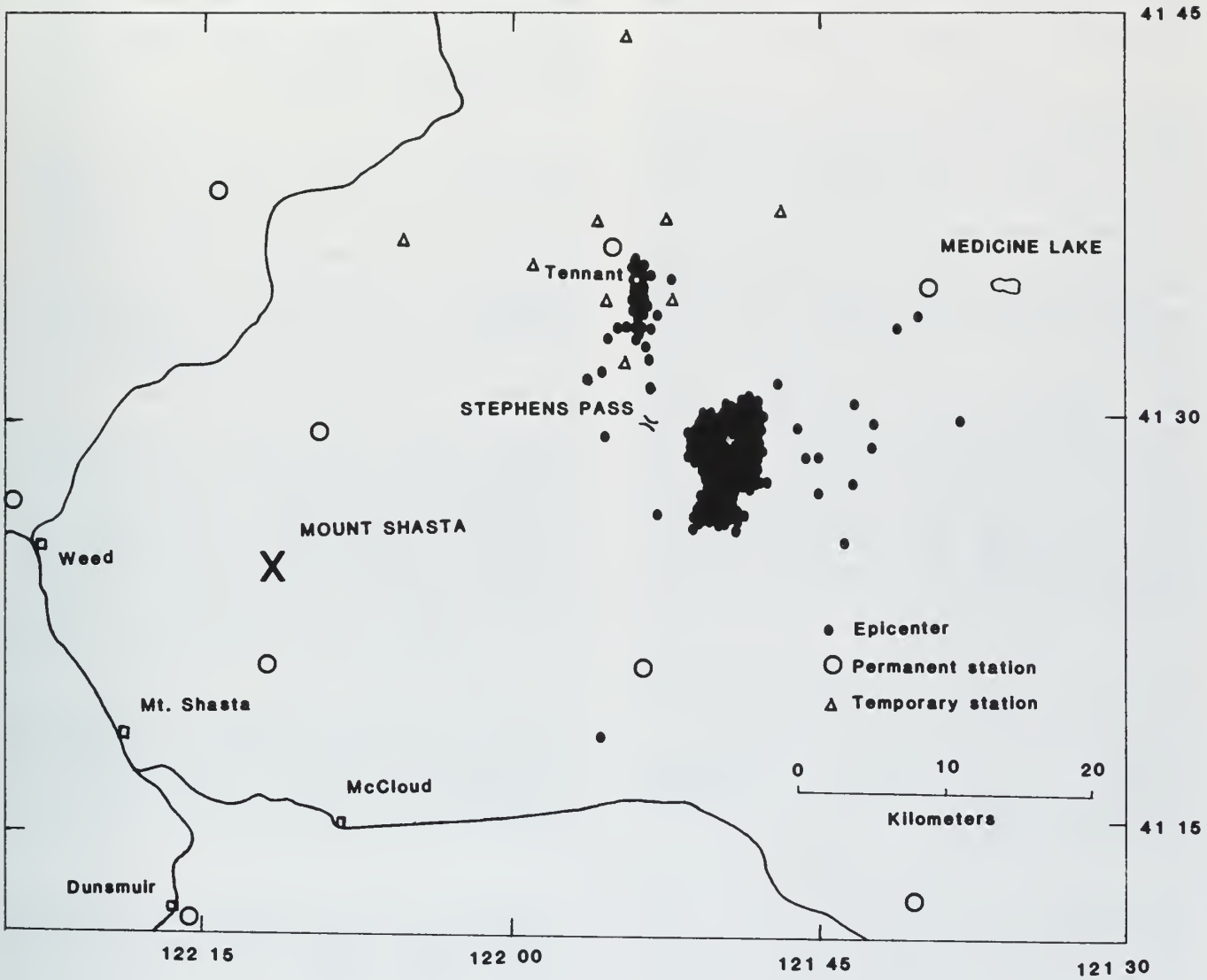


Figure 8. Epicenters of Stephens Pass and Tennant earthquake swarms of 1978 (southern cluster of epicenters) and 1981 (northern cluster), (after R. Cockerham, U. S. Geological Survey, unpublished data, 1982.)

some sporadic earthquake activity over the years. It is on the northern boundary of one of California's major seismic zones.

Question: Has there been any attempt to make volumetric determinations of magma outpourings with respect to time?

Christiansen: Yes; that attempt is going on just now. A point I would like to make in the talk is that for the California Cascades, until about the last five or six years, we have been entirely dependent upon data that was obtained in the 1920s and 1930s by a very few people. Some real pioneering work was done by Howel Williams and Charlie Anderson and a few others, supplemented, of course, by some specific locality studies, but, really, all of our comprehensive data came from those early studies, and we are just now re-examining these areas and getting the kind of data you're asking about. I think that is one of the very important things for us to do; that is, gathering quantitative information such as volumes of eruptions.

Question: On the definition of "active volcano," if we have development of fumarolic or hydrothermal activity on a volcano, but no eruptions in the past two-thousand years, would you consider it an active volcano?

Kilbourne: If the only activity that has been documented is that of an active fumarole, no, I would not call that an active volcano.

Question: What is Bob's opinion?

Christiansen: Well, I really have trouble with this term, "active volcano," and I am not sure it is a terribly useful term. Quite honestly, I think that we tell ourselves more if we say, "a volcano that has erupted in the last two-thousand years" or "an active fumarole field," or whatever, than we do by arbitrarily defining a term like "active volcano" and then trying to apply it. I think it is very likely that there are many volcanoes that erupted in the last two-thousand years that will never erupt again. And I think that there are volcanic systems that have not erupted in the last two-thousand years that are very likely to erupt in the future. I am worried that use of the term "active volcano" may fool us sometimes. I'd rather be more specific when categorizing volcanos.

Kilbourne: I realize what you're saying about "active volcano" being a poorly understood term, or a potentially dangerous term. On the other hand, the public does understand the term "active" as meaning dangerous in the case of a volcano, and since we sometimes deal with the public in crisis situations, I'm proposing that we as scientists standardize our definition. I am not aware of many volcanos or volcanic regions that have not erupted in the last two-thousand years that have somehow suddenly become active. The eruptions of Paracutin in Mexico (1943) and Surtsey in Iceland (1964) are often cited as surprise eruptions, but even these occurred in active volcanic terrains as I would have us define them, with the 2,000-year datum. I don't think anyone could name a volcano that has erupted in the last two-thousand years that they would swear would not erupt again; so, therefore, I would like to use this term only in this fashion; i.e., with a rigid definition of eruption in the last 2,000 years.

Question: Would you elaborate on your statement that Mount Shasta was like Mount Mazama in its nature?

Christiansen: The point I was trying to make is one that I think many other people have made: that volcanic systems are of different types, and that some seem to have a capability of evolving in the direction of a climactic sort of pyroclastic eruption and caldera collapse related to it. The reason I think Shasta could be in that class is because it: 1) has evolved in a rather complex manner for a long period of time indicating that there is a substantial, active heat source that is continuing to evolve

magma beneath that region; 2) eruptions have repeatedly evolved to silicic compositions, as seems to be typical of most such volcanoes that erupt large volumes of pyroclastic materials; and 3) the volcano has had a long period of relative quiescence. "Silicic," in this case, is also a fairly loose term, but I mean more silicic than the typical sort of mafic andesites or basaltic andesites that we see a lot of. This complexity of evolution and diversity of lava compositions is the principal thing that suggests that this may be a volcano like Mazama was before it entered its climactic episode.

Question: Isn't there some aeromagnetic evidence that there is magma within the Shasta Volcano?

Christiansen: There has been some interpretation based upon the aeromagnetic data that is consistent with the main cone of Mount Shasta being the hottest part of the volcanic edifice. As you are aware, this is an ambiguous type of data. It is only a consistency argument and not really what I would regard as evidence for magma.

Question: Dr. Kilbourne, one of your slides dealt with the source of the Carbon-14 of a lava flow and it shows 280° and 500° isotherms. Is that in Fahrenheit or Centigrade?

Kilbourne: It is Centigrade. The significance is that above 500°C, wood burns to ash in the presence of oxygen. The wood is preserved for us to use in age-dating if the temperature does not go above 500°C. Above 280°C, wood will char, and in a closed environment, turn to charcoal.

Question: Dr. Christiansen, you identified the Lassen area as potentially one of the most dangerous in the Cascades. Has the USGS or the state increased their monitoring of this area recently?

Christiansen: What I said is a value judgment of a sort. Nevertheless, most people would regard Lassen as a dangerous part of the Cascades and one of the most dangerous. The USGS in recent years has augmented the seismic network there, and just last summer the first set of measurements of a geodetic network were undertaken. These will be used as the basis for comparison with future data. These are very skeletal efforts, and, certainly, more is called for. In addition, there is an ongoing study of the geology and volcanic hazards of Lassen Park by Mike Clynne and Patrick Muffler. That work has just begun and will be continuing for the next few seasons, and I hope to be able to participate in it too. These efforts are aimed at hazard assessment, but, again, in terms of monitoring specifically, the USGS effort is skeletal or minimal.

McBirney: In looking at the geologic record in a large mature volcano and trying to piece together the past history, do you think we get an unbiased representation of the different types of activity that that volcano has gone through, due to the fact that the large ash eruptions are usually less likely to be preserved and they produce material which the geochronologist usually doesn't want to fool with?

Christiansen: I think the answer is implicit in the question. Indeed, we do get a biased view of the evolution of a volcanic system like this. This points out something that I personally have found useful in my own work in the last few years, and I think has been borne out in a number of instances, including, specifically, Mount St. Helens. There are different complementary approaches that ought to be utilized in looking at the geologic record as a basis for hazards analysis. One is the sort of traditional mapping and evolutionary study of a volcano such as I am attempting to undertake at Mount Shasta. The complementary aspect is the stratigraphic approach: looking at the record of what has happened on the flanks of the volcano, and also looking for the record of even the small events that would be represented, perhaps indirectly, by things such as mudflows. This is the approach Dan Miller is taking at Mount Shasta, and I think that both of us feel that by working closely together between a stratigraphic/soils/

surficial-geology approach and a volcanic-evolution/petrology/geophysical approach, we get much more information than either approach by itself possibly could.

Kilbourne: I think we get a good representation of the hazardous types of eruptions. The larger eruptions are the ones we're really worried about. Small things like the 1951 mud-volcano event in Surprise Valley or the small 1910 eruption in the Medicine Lake Highlands area don't leave any record; unless they're observed, they aren't dated.

REFERENCES CITED

Anderson, C.A., 1941, Volcanoes of the Medicine Lake Highland, California: University of California Publication, Department of Geological Science Bulletin, v. 25, p. 347-422.

Bacon, C.A., 1982, Eruptive history of Mount Mazama, Cascade Range, U.S.A.: Journal of Volcanology and Geothermal Research (in press).

Bennett, J.H., Sherburne, R.W., Cramer, C.H., Chesterman, C.W., and Chapman, R.H., 1979, Stephens Pass earthquakes, Mount Shasta, August, 1978: California Geology, v. 32, p. 27-34.

Bowen, P.A., 1978, Pleistocene volcanism near Lassen Peak, California: Geological Society of America Abstracts and Program, v. 10, p. 97.

Christiansen, R.L., Kleinhampl, F.W., Blakely, R.J., Tuchek, E.T., Johnson, F.L., and Conyac, M.D., 1977, Resource appraisal of the Mount Shasta Wilderness Study Area, Siskiyou County, California: U.S. Geological Survey Open-File Report 77-250, 53 p.

Christiansen, R.L., and Miller, C.D., 1976, Volcanic evolution of Mount Shasta, California: Geological Society of America Abstract Program, v. 8, p. 360-361.

Christiansen, R.L., and Peterson, D.W., 1981, Chronology of the 1980 eruptive activity, in Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 17-30.

Crandell, D.R., 1972, Glaciation near Lassen Peak, northern California, in U.S. Geological Survey Research, 1972: U.S. Geological Survey Professional Paper 800-C, p. C179-C188.

Crandell, D.R., Mullineaux, D.R., and Miller, C.D., 1979, Volcanic-hazard studies in the Cascade Range of the western United States, in Sheets, P.D., and Grayson, D.K., editors, Volcanic activity and human ecology: Academic Press, New York, p. 195-219.

Crandell, D.R., Mullineaux, D.R., Sigafoos, R.S., and Rubin, M., 1974, Chaos Crags eruptions and rockfall-avalanches, Lassen Volcanic National Park, California: U.S. Geological Survey Journal of Research, v. 2, p. 49-59.

Day, A.L., and Allen, E.T., 1925, The volcanic activity and hot springs of Lassen Peak: Carnegie Institute of Washington, 190 p.

Donnelly-Nolan, J.M., Ciancanelli, E.V., Eichelberger, J.C., Fink, J.H., and Heiken, G., 1981, Roadlog for field trip to Medicine Lake Highland, in Johnston, D.A., and Donnelly-Nolan, J., editors, Guides to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geological survey Circular 838, p. 141-149.

Eichelberger, J.C., 1975, Origin of andesite and dacite: Evidence of mixing at Glass Mountain in California and at other circum-Pacific volcanoes: Geological Society of America Bulletin, v. 80, p. 2213-2236.

Eichorn, E.F., 1954, The Mount Shasta story (revised edition): Mount Shasta Herald, Mount Shasta, California.

Finch, R.H., 1927, Cause of Lassen mud flows: The Volcano Letter, n. 118.

Finch, R.H., 1930, Activity of a California volcano in 1786: The Volcano Letter, n. 308, p. 3.

Finch, R.H., and Anderson, C.A., 1930, The quartz basalt eruptions of Cinder Cone, Lassen Volcanic National Park, California: University of California Publications Department, Geological Science Bulletin, v. 19, p. 245-273.

Fountain, J.C., 1979, Geochemistry of Brokeoff Volcano, California: Geological Society of America Bulletin, pt. 1, v. 90, p. 294-300.

Heiken, G., 1976, Depressions surrounding volcanic fields: A reflection of underlying Batholiths?: Geology, v. 4, p. 568-572.

Heiken, G., and Eichelberger, J.C., 1980, Eruptions at Chaos Crags, Lassen Volcanic National Park: Journal of Volcanology and Geothermal Research, v. 7, p. 443-482.

Hill, M., and Enghoff, E.L., 1976, A California jokulhaup: California Geology, v. 29, p. 154-158.

Kane, P.S., 1980, Through Vulcan's eye: The geology and geomorphology of Lassen Volcanic National Park: Mineral, California, Loomis Museum Associates, 118 p.

Klein, F.W., 1979, Earthquakes in Lassen Volcanic National Park, California: Seismological Society of America, v. 69, p. 867-875.

LaFehr, T.R., 1965, Gravity, isostasy, and crustal structure in the southern Cascade Range: Journal of Geophysical Research, v. 70, p. 5581-5597.

Loomis, B.F., Pictorial history of the Lassen volcano: Mineral, California, Loomis Museum Association, 96 p.

Luedke, R.G., and Smith, R.L., 1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-1091-C.

Lydon, P.A., Gay, T.E., Jr., and Jennings, C.W., 1960, Geologic map of California, Westwood [Susanville] sheet: California Division of Mines, scale, 1:250,000.

Miller, C.D., 1978, Holocene pyroclastic-flow deposits from Shastina and Black Butte, west of Mount Shasta, California: U.S. Geological Survey Journal of Research, v. 6, p. 611-624.

Miller, C.D., 1980, Potential hazards from future eruptions in the vicinity of Mount Shasta volcano, northern California: U.S. Geological Survey Bulletin 1503, 43 p.

Muffler, L.J.P., Bacon, C.R., and Duffield, W.A., 1982, Geothermal systems of the Cascade Range: Auckland, New Zealand, Pacific Geothermal Conference, November 1982, in press.

Williams, H., 1932, Geology of the Lassen Volcanic National Park, California: University of California Publications Department Geological Science Bulletin, v. 21, p. 195-385.

Williams, H., 1934, Mount Shasta, California Zeitschr. Vulk., v. 15, p. 225-253.

Williams, H., 1942, Geology of Crater Lake National Park, Oregon, with a reconnaissance of the Cascade Range south to Mount Shasta: Carnegie Institute of Washington Publication 540, 162 p.

Williams, H., 1949, Geology of the Macdoel quadrangle: California Division of Mines Bulletin 151, p. 7-60.

DESCRIPTION OF U.S. GEOLOGICAL SURVEY STUDIES OF POTENTIAL HAZARDS FROM FUTURE ERUPTIONS IN CALIFORNIA

C. Dan Miller
U.S. Geological Survey
Denver Federal Center, Colorado

Locations of potential hazards from future volcanic eruptions in California are being evaluated by the U.S. Geological Survey. The studies outline volcanic-hazards zones at scales of 1:500,000 and 1:5,000,000 in the eight areas of the State in which volcanoes have been active during the Holocene. The likely nature, scale, and effects of future eruptions and the basis for the hazard zonation are being evaluated in the study.

Only volcanic vents younger than about 100,000 years have been considered in the study. These vents are divided into two broad groups according to age: (1) Late Pleistocene vents -- vents that have been active between about 100,000 and 10,000 years; and (2) Holocene vents -- vents that have erupted during the last 10,000 years. Volcanoes in California are further subdivided broadly according to eruption type and the composition of products erupted at each vent. The categories include: (1) vents that have erupted products that range in composition from basalt to basaltic-andesite; (2) vents that have erupted products that range from andesite to rhyolite; and (3) volcanic vents at which there have been phreatic or phreatomagmatic eruptions.

Zones showing potential volcanic hazards are described and shown only for vents that have erupted during Holocene time. For volcanoes that last erupted between 10,000 and 100,000 years ago or earlier, data are considered to be too scanty and events occurred too long ago to be used as a basis for forecasting the kind, scale, and frequency of eruptions in the near future.

Volcanic-hazards zones portray potential hazards from flowage phenomena that include lava flows, pyroclastic flows, mudflows, and floods; from surge, including base surge, eruptions; and from falling ash (tephra). Hazard zones for each volcanic vent are based primarily on events that have occurred in the past (precedented events) at that vent or volcano. The kinds of scales of past events were determined from the literature and/or by geologic studies at each vent. Those events form the basis of the zones for precedented hazards. In addition, at several locations in California, hazard zones are portrayed for eruptions that are significantly larger than locally precedented events, but such eruptions are considered possible because of the nature and history of the volcanic system. At these locations, hazard zones for unprecedented events have been constructed using as a model the large caldera-forming eruptions that occurred about 7,000 years ago at Mount Mazama in Oregon.

Tephra-hazard data are portrayed for several vents in California at which very large eruptions of tephra are regarded as possible. These tephra-hazard data on thickness versus distance from the vent are based on data from moderate, large, and very large tephra eruptions of the past at Mount St. Helens, Washington; Mount Mazama, Oregon; and Bishop, California, respectively.

DISCUSSION

Question: Did you try to overlay all the various types of hazards on a single base, or

are some, like the pyroclastics, to be handled on another base?

Miller: What I have at this time is a combined flowage hazards zone, shown in orange, that includes hazards of lava flows, pyroclastic flows, mudflows, and floods. Obviously, different areas within that orange zone would be endangered by different phenomena. I have shown surge and base surge hazards zones as a separate color, and hazards from basaltic eruptions and cinder cones in yet a third color. So, a number of different kinds of zones are shown on this map.

Question: Will this be made available by the Survey?

Miller: I hope we can publish it as soon as possible.

Question: You seem to have portrayed the hazards in the Clear Lake area as rather minor. Why is that?

Miller: In the Clear Lake area in Holocene time, there have only been phreato-magmatic eruptions of basaltic or other mafic types of materials. In other words, none of the silicic activity is as young as Holocene time. As mentioned earlier, I did not portray hazards from events such as those which occurred before about 10,000 years ago. This does not mean, however, that it is not possible to have explosive silicic eruptions in the Clear Lake area. I think the last silicic eruption there was about 44,000 years ago. On the basis of such skimpy data, we don't have much to go on as to what might happen there in the near future or for land-use planning purposes. I should also point out that in the Coso Range there are late Pleistocene events, but no Holocene ones. Thus, I have not shown hazard zones there, although as Roy Bailey mentioned yesterday, there probably is a magma chamber in that system. Based on my fieldwork, I think that the last eruptions in the Coso area have been more than 30 or 40 thousand years ago. Again, it is possible that there may be future eruptions, but they may occur far in the future. For present purposes, I have not shown hazards zones there. These are things open to discussion, and it may be that my philosophy could change somewhat.

IMPACTS OF THE MOUNT ST. HELENS ERUPTION ON INDUSTRY

Dr. Clive F. Kienle, Senior Geologist
Foundation Science, Inc.
Portland, Oregon

INTRODUCTION

The major direct impacts of the 1980-81 eruptions on industry were a result of the giant landslide, the laterally directed pyroclastic eruption, and mudflows generated during the May 18, 1980 eruption. Lesser but significant impacts resulted from the tephra generated by the May 18 and subsequent explosive eruptions during 1980. The giant landslide and lateral pyroclastic eruption (commonly called "the blast") destroyed or severely damaged nearly 500 square kilometers of timberland, 300+ kilometers of logging roads, over 50 bridges, 30 kilometers of logging railroad, and several decking and milling facilities. Mudflows generated by the blast caused much of the damage near the volcano as well as in the Toutle, Cowlitz, and Columbia river valleys. Traffic on Interstate 5 and parallel railroads was interrupted, port facilities at Longview and Kelso, Washington, were damaged, and shipping on the Columbia was halted by the mudflows. The Port of Portland, Oregon was closed to deep-water shipping for several weeks.

Ashfall from the May 18 eruption closed airports and highways downwind of the volcano for up to several days. Some electrical transmission facilities were affected by damaged internal combustion engines and air conditioners throughout a large area. Explosive eruptions after May 18 also resulted in airport closures, damage to semiconductor manufacturing, and massive cleanup expenditures in the Portland metropolitan area.

There have also been major indirect impacts. These include expenditures by industries to protect themselves from volcanic hazards, as well as losses and expenditures necessitated by various governmental requirements. Protective expenditures include extensive volcano hazard and monitoring studies by local electrical utilities for the Trojan Nuclear Plant and Swift Reservoir and design and operating modifications for these facilties. Weyerhaeuser Company also sponsored studies of hazards near the volcano and implemented elaborate protective measures for their employees. Governmental restrictions have been largely aimed at the control of access to areas near the volcano; at times this access control has interfered with efforts of scientists to study the volcano. The desire to preserve much of the devastated area north of Mount St. Helens has resulted in the loss of millions of board feet of salvageable timber. In addition, regulatory agencies have required studies of possible impacts of the volcano on dams and power plants -- studies that have cost hundreds of thousands of dollars. Direct impacts, in the form of mudflows and minor eruptions, may continue for several years. Indirect impacts, in the form of expenditures by societies reassessing their security and state of hazard preparedness in the western United States, may continue for decades.

INITIAL ACTIONS BY INDUSTRY

Preparations for a possible eruption of Mount St. Helens began to be made by power companies, reservoir operators, and timber companies in the area on March 20, 1980. On March 27, owners of power-generating facilities in the area began to make some contingency plans in the light of

Figure 1. Ash collector, Smith Creek Butte, six miles east of the crater. This impromptu ash collector survived a trial exposure to 300° C heat, and yielded the only samples of May 18 tephra in which magmatic and nonmagmatic lithic tephra could be separated with certainty. Note installation of crossarm insulators and conductors in the background.

forecasts (made by the U.S. Geological Survey [USGS] and the University of Washington) of an ever-increasing likelihood of a major eruption.

The first concern was to determine if an eruption was, indeed, likely to occur and if an eruption was probable. The companies needed to know the most likely pattern of events. Would it be similar to past eruptions in the Cascades? They wanted to know what was the worst that they could expect so that contingency plans could be made. Those companies most concerned were the operators of the Trojan Nuclear Power Plant, located 35 miles west of the mountain, and Swift Reservoir, which is on the south flank of the mountain.

Foundation Sciences, Inc. (FSI), set up a program with Portland General Electric Company (P.G.E.) to monitor the small-scale eruptions of the mountain which began on March 27, 1980. This program paralleled that of the USGS but was necessary in order to collect and analyze data and send it to the Nuclear Regulatory Commission (NRC) within a few hours of each eruption. The NRC was concerned about the possible effects of large eruptions on the Trojan Nuclear Plant. As discussed later, the plant suffered no ill effects from the "Big Blast" of May 18.

A part of the monitoring program was collection of ash from the phreatic eruptions which preceded the major eruption. Ash was first collected on mylar sheets with small berms around them, but later, plastic wading pools were employed (Figure 1). These proved to be far superior to the mylar.

The purpose of the ash study was to get information on the physical and chemical properties of the ash and to determine what effects it could have on power-generating and transmission facilities. It was found that no juvenile material was ejected prior to the May 18 event. The early pyroclastic material consisted of partially decomposed lithic debris disseminated by phreatic explosive action. The P.G.E. also set up simulated transmission lines to see what effect the ash would have on conductors and insulators. Based on data from the monitoring program and study of other historic ashfalls, P.G.E. developed a program to clean up and mitigate ashfall effects on their system.

Preliminary studies by Pacific Power and Light indicated that large mudflows into Swift Reservoir could possibly overtop the dam. Consequently, Swift Reservoir was drawn down to accommodate up to 100,000-acre-feet of mudflows and floods. This was done prior to the major eruption on May 18. After the May 18 eruption, the powerhouse was shielded to protect it from any blast effects.

THE HORIZONTAL BLAST

On May 18, 1980, two magnitude-5 earthquakes occurred in the area of Mount St. Helens. One of these quakes triggered a massive landslide on the north side of the mountain, and this slide was immediately followed by a complex major explosive eruption. The initial explosions are commonly known as "the blast." The biggest long-term problems associated with this eruption were the destruction of about 590 km of watershed by "the blast" and the debris avalanche, which advanced northward several kilometers, then down the Toutle River Valley to the west. Mudflows (lahars) developed out of the slide and caused additional damage downstream.

Within the area of the blast, about 60,000 acres of trees belonging to Weyerhaeuser, and more than 100,000 acres of U.S. Forest Service land were blown down or stripped. Thirteen miles from the crater (Figure 2), trees showed effects of the blast in distinct zones with effects ranging from trunks snapped off near the base in the bottom of the valleys to unaffected trees near the higher ridges. The evidence shows very definitely that the destructive agent was a hot, pyroclastic flow. Near the source, it overrode, but was influenced by, topographic highs. Further away, it was constrained to topographic lows but was mobile enough to surmount smaller topographic barriers. However, most of the timber within the "blast" could be salvaged if the market for it were not so low. Interpretations of the adversity of the "blast" are available in Lipman and Mullineuax (1981) and Kienle (1980).

Figure 2. This photo, thirteen miles from the crater, shows snapped-off trees and the clearly defined singe zone. Destructive effects distributed in sharp zones illustrating that the horizontal blast, at least in this area, was essentially a hot, mobile pyroclastic flow.

Figure 3. The downstream toe of an impoundment being cut into by the river. A new groundwater level is being established in the material and is filling small explosion craters on the downstream face. Evidence of piping failures are appearing.

MUDFLOWS

In the North Fork of the Toutle River, mudflows mobilized from the debris avalanche were also destructive. Fifty bridges were destroyed along with 300+ miles of roads and 30 miles of logging railroads. Gondola cars on the Weyerhaeuser Company railroad were picked up and moved about five miles, illustrating the density and force of the mudflows. Detailed descriptions of the mudflows are presented by Kienle (1980) and Janda and others (1981). If rainfall had not been unusually light prior to the eruption, the baseload of the streams would have been greater, and the destruction would have been more extensive.

South of the mountain, relatively minor mudflows built a small delta in Swift Reservoir but did not cause significant damage. No damage occurred to Swift Dam or Powerhouse.

The Cowlitz and Columbia rivers were clogged with debris from the mudflows for several miles. The Columbia was closed to deep-water shipping from May 19 to June 15. The closure of the Port of Portland cost $7 - $10 million per day. Thirty-one ships were trapped in the port during that period, and 50 ships were diverted.

VOLCANIC DEBRIS PROBLEMS

The Corps of Engineers entered the picture shortly after the May 18 eruption. The Cowlitz and Toutle rivers were filled with mudflow debris, and the side drainages were either filled or dammed with mudflow levees, so the tributaries flooded many of the surrounding areas. The Corps immediately began constructing impoundments on the North and South Forks of the Toutle River to trap the silt and lessen the downstream impacts. The Corps also dredged the Cowlitz to restore its pre-eruption capacity and the Columbia to open the shipping channel. Total cost of Corps work to date is in excess of 0.5 billion dollars.

Probably the highest potential hazard from the May 18 eruption resulted far upstream, due to the formation of natural impoundments or lakes formed in the debris avalanche material (Figure 3). If these natural dams were to overtop and burst, the resulting mudflows downstream could be much more severe than the original lahars of the May 18 eruption. The Corps of Engineers had the job of designing and constructing outflow structures in these impoundments to prevent their failure. Piping failures are beginning to show up in some of these dams. The two major impoundments are the Coldwater Lake (60,000 acre ft.) and the South Fork Castle Creek Lake (300 acre ft.).

There was significant erosion of the debris this winter with the early and heavy storms. Streams are re-establishing themselves in their old courses by headcutting and slumping of banks. Bank erosion and slumping is resulting in dissection of the upper portions of the debris fill. Downstream movement and deposition of sediment is clogging the lower reaches of the Toutle River and is thus creating potential flood hazards.

ASHFALL DAMAGE

Ash was a minor problem in the area of Mount St. Helens, but some damage was done in the Yakima, Spokane, and Ritzville areas, where some internal combustion engines and air conditioners were damaged (Figure 4). In addition, the heavy sediment influx clogged storm-sewer systems, sewage treatment plants, and water purifications systems. The thickness of the deposit and size of grains falling generally decreased away from the volcano. However, the thickest deposits occurred in the area of Ritzville, where a wide range of grain sizes fell together as a result of agglomeration processes. The May 25 and June 12 eruptions produced small ashfalls in the City of Portland; these ashfalls resulted in a multi-million-dollar cleanup problem as well as contamination problems for the semiconductor industry.

DISCUSSION

Question: Is the threat of mudflows greater or less this year?

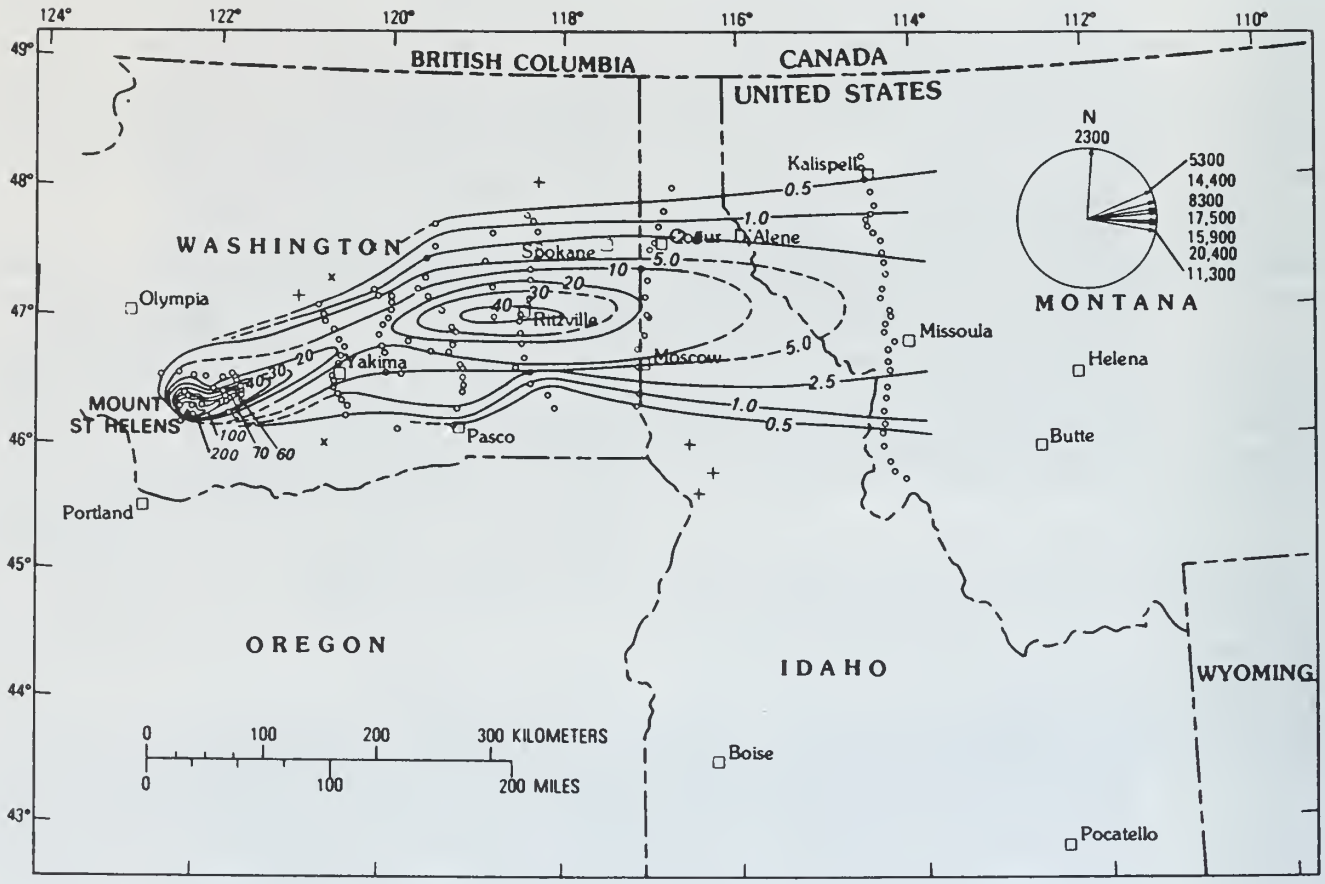


Figure 4. Isopach map of air-fall ejecta on May 18. Lines represent uncompaced thickness, in millimeters. +, light dusting of ash; x, no ash observed; circles, observation sites. Circular diagram shows average directions toward which wind was blowing, for different altitudes, at 1020 PDT on May 18, at Spokane, Washington. Data from U. S. National Meteorological Service. In the Ritzville area, damage was mainly to equipment and social organization. The ashfall affected people's health and created disorganization to social structures, but only one death was directly attributed to ashfall (a cropduster crashed into a BPA line, apparently, because of reduced visibility). Figure from Sarna-Wojcicki and others, 1981, U. S. Geological Survey Professional Paper 1250, p. 583.

Kienle: There is a potential for more problems this year due to expected warmer weather and higher rainfall. More importantly, the debris is saturated and drainages are returning to their old channels, which increases their ability to carry water and material. This could lead to greater runoff, slumping of banks, and creation of new mudflows. The problem would be increased further if some of the debris impoundments fail.

Bob Matthews: Did I hear you say the Swift Reservoir was not lowered until after the May 18 eruption?

Kienle: No. I said the reservoir had been drawn down to a capacity of 100,000 acre feet before the May 18 eruption. What was not done until after the eruption was making that dam a remote-controlled operation.

Question: What would have been the effect on Trojan if the blast had gone that way?

Kienle: An attempt was made to model that occurrence. The conclusion was that it would not be a desirable thing to happen, even though modeling indicated that the blast from Mount St. Helens would fall short about ten miles of the power plant. The ash would not damage the reactor containment structure, which was designed to withstand a hurricane, but the appurtenant structures and the transformers might be damaged.

Question: What about the cooling water? any impacts?

Kienle: One of the recommendations we made to Trojan was to find a back-up water supply. As the plant was built, it had two water supplies: a cooling tower with a large sump in it, and the Columbia River. The sump was large enough to operate the plant for two weeks. In the event the intake on the river was plugged with mudflow debris, we recommended that a large decorative pond containing 80 acre feet of water be converted into a reserve water supply. The people at Trojan have had to do a lot of work to convince McBirney and others reviewing their work that they are, indeed, capable of withstanding a large volcanic eruption.

Question: Was there any problem with high-tension power lines?

Kienle: Not with the power lines directly, but some of the insulators were found to have problems. A kind of plastic insulator, used by Clark County and other small public utility districts, did not hold up well to wet, conductive ash. They would etch out and allow flashing, but conventional glass insulators held up well, especially in vertical configurations.

REFERENCES CITED

Janda, R.J., Scott, K.M., Nolan, K.M., and Martinson, H.A., 1981, Lahar movement, effects, and deposits, in Lipman, P.W., and Mullineaux, D.R., The 1980 eruption of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 461-478.

Kienle, C.F., 1980, Evaluation of eruptive activity at Mount St. Helens, Washington, March through June 1980: Foundation Sciences, Inc., unpublished report prepared for Portland General Electric Company.

Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250.

Sarna-Wojcicki, A.M., Shipley, Susan, Waitt, R.B., Dzurisin, Daniel, and Wood, S.H., 1981, Aerial distribution, thickness, mass, volume, and grain size of air-fall ash from the six major eruptions of 1980, in Lipman, P.W., and Mullineaux, D.R., The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 577-600.

REALISTIC VOLCANIC HAZARDS ASSESSMENT AND THE IMPORTANCE OF FREQUENCY/EXPLOSIVITY RELATIONS

Dr. Alexander R. McBirney
University of Oregon

ABSTRACT

Assessment of volcanic risks has two very different aspects: short-term forecasting of impending eruptions based on monitoring the current state of a volcano, and longer-term evaluation of the nature of future activity based on geological and geophysical studies. Despite the great progress made in monitoring and interpreting signs of unrest, much remains to be learned about the more difficult task of estimating the probabilities and possible nature of eruptions from long-dormant volcanoes. The crux of the problem lies in the fact that the volcano that presents the greatest danger is often the one that has had a long period of repose with little or no historic activity to use as a basis for anticipating patterns of future eruptions.

To treat such volcanoes in a purely statistical way is not only simplistic; it can be highly misleading. One can compile statistics on certain types of volcanoes and show that, on a world-wide or regional scale, certain types of eruptions have occurred with a certain frequency during a given interval of recorded history. But this may be meaningless in the case of an individual volcano with its own unique characteristics at a particular stage of evolution. The practice of taking an eruption of one volcano as a model for the possible behavior of another is not a rational substitute for detailed geological and geophysical studies of each individual volcano.

In most instances, the question we are trying to answer is not whether the volcano will erupt, but whether it will erupt violently. To determine this, one needs to establish the nature of the magmatic system and the stage to which it has evolved. By determining the interval of repose since the last eruption, it is possible to provide a more intelligent estimate of the probabilities of a major explosive eruption, provided, of course, that evidence can be found for continuing magmatic activity at depth. Recently developed geophysical techniques may soon make it possible to do this by detecting large bodies of shallow magma.

Perhaps the most important need is an improved understanding of the basic physical mechanisms governing volcanic activity. By combining theoretical and experimental studies with good observational data, such as those coming from Mount St. Helens, Etna, and Kilauea, we are finally approaching the point where we can make realistic assessments of volcanic hazards.

INTRODUCTION

Since the eruption of Mount St. Helens, there has been a tremendous increase in the awareness of volcanism in the western United States. It has resulted in a somewhat distorted view as to what volcanoes do. The average person, when he hears about potential eruption in the Cascades, probably thinks of the 18th of May 1980, but volcanoes vary widely in their behavior and it is difficult to use any one as a model for another. The varieties of hazards they create was brought out very well today by Rick Kienle.

When we think of an eruption of a lava flow or an ash eruption, we should bear in mind that these are common events that occur almost weekly throughout the Circum-Pacific, and people who live with these volcanoes seldom give them a second glance. When we speak of hazards in this part of the world, the hazard is not so much the flow of lava coming down the volcano as the flow of television crews and lawyers coming from the other direction. I would like to put this problem into perspective by giving a brief overview of active volcanoes and how their behavior relates to what we would consider hazardous types of eruptions.

Studies of hazards fall into two general categories. First, there is the day-to-day monitoring of volcanoes of the kind being conducted now at Mount St. Helens or Kilauea. This surveillance allows us to keep track of what is going on in the interior of that volcano and, perhaps, foresee something that may be imminent. There is another level of study which takes a much more long-range view. It consists of studying the volcano, its past history, and trying to deduce something about its individual personality. From that, we may be able to make long-range forecasts of what can be expected from that volcano. Examples of this latter type are Crandell and Mullineaux's study (1978) of Mount St. Helens and Christiansen and Miller's current study of Mount Shasta.

ERUPTION FREQUENCY GROUPS

Volcanoes can be divided into three broad groups. First, there is the type that erupts with great frequency -- let's say Mt. Etna, Kilauea, and some of the volcanoes of Central America. These are the ones that are most likely to be closely monitored; they are also the ones which can be predicted most easily. This is because we have established a pattern of behavior: we have developed techniques for forecasting eruptions by watching the workings of the volcano over a period of many years. The second group probably includes the largest number of volcanoes of interest to volcanologists. This is the group that has some historic activity but, perhaps, not with a frequency that would justify regular monitoring. It simply is not practical to monitor every volcano, and those which have not been active recently are not going to be watched closely, unless there is some unusual event that draws our attention to that particular volcano. Finally, the most difficult group to deal with is that which consists of volcanoes having no historic activity and a long period of repose since the last eruption. These are the ones we refer to when we try to decide whether a volcano is "extinct" or "dormant." The last two groups of infrequently erupting volcanoes are the ones that we can study only by the second method. We must study the past history of the volcano and try to deduce its pattern of activity.

Very few data are available on the frequencies of eruptions of these three groups of volcanoes. George Walker (1974) attempted a statistical study of the frequencies of eruptions from 180 volcanoes for which he had fairly good historical records for a period of 500 years. From these data, he came up with the following statistics. The "median volcano" in the group had one eruption every 220 years. Twenty percent of the volcanoes had less than one eruption every 1,000 years; two percent had less than one eruption every 10,000 years; and by extrapolating the data (and this is an enormous extrapolation) he concluded that one percent has less than one eruption every 50,000 years.

EXPLOSIVITY RELATIONS

Data of this kind can be coupled with an index of explosivity (Figure 1). This was done by the Smithsonian Institute in a recent compilation of the historic eruptions of volcanoes throughout the world (Simkin and others, 1981). The diagram is a comparison between the magnitude of energy released in a large explosive eruption and the period of repose between eruptions. At the bottom of the figure are eruptions of low-explosivity -- lava flows and very small explosive eruptions with mild ash falls. Toward the top of the figure are eruptions of larger- and-larger magnitude up to the really colossal event like the one responsible for Crater Lake. As the explosivity increases, the repose time gets longer. The

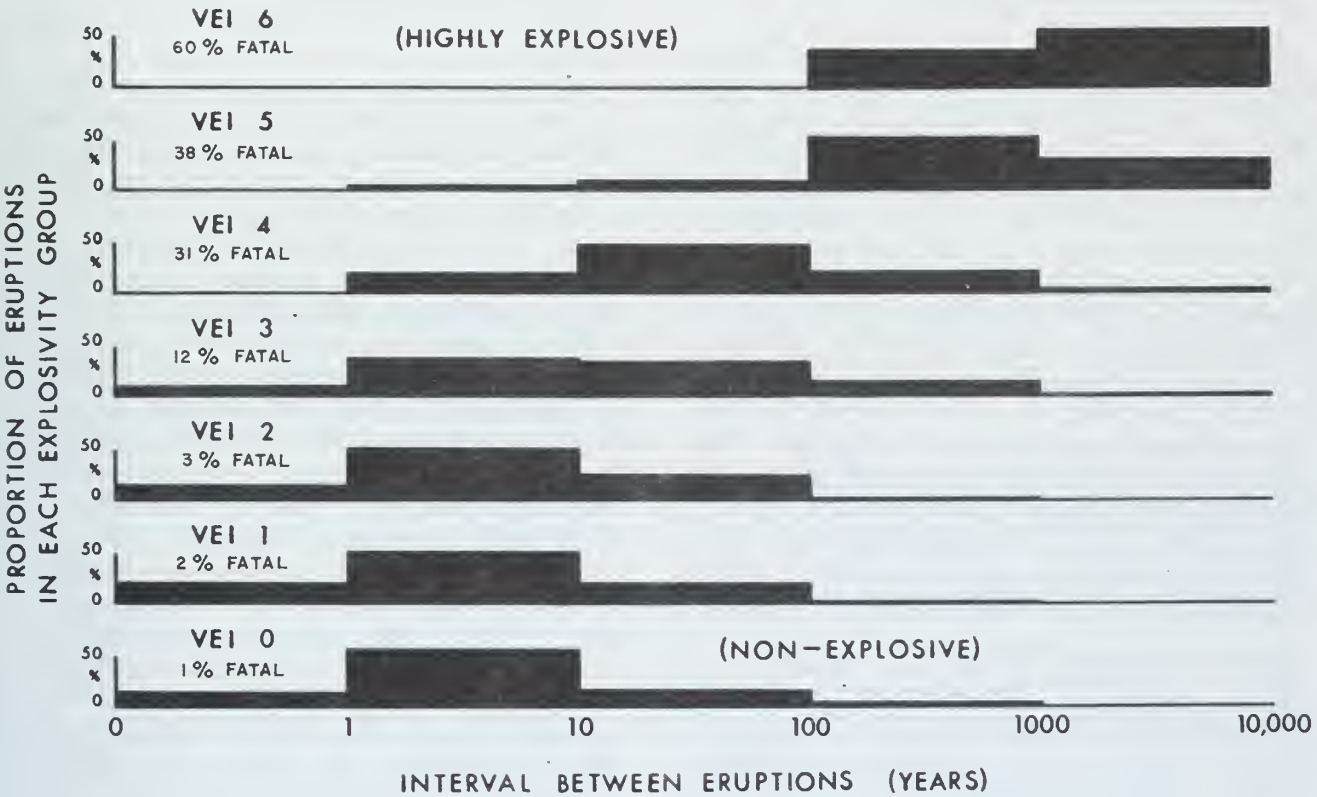


Figure 1. Relation of explosivity and time intervals between eruptions. For each VEI (Volcanic Explositivity Index) category eruptions are grouped by time interval from start of previous eruption. The number of eruptions in VEI groups 0 to 6 are, respectively: 354, 338, 2882, 617, 102, 19, and 8. For each group, the percentage of historic eruptions that have produced one or more fatalities is also shown. Figure (Simpkin and others, 1981) courtesy of the Smithsonian Institution.

long-dormant group of volcanoes is the one that Walker deduced to erupt once every 10,000 years or more. They are also the ones for which we have the least record, the longest period of repose, and, most important, they are the volcanoes that are most likely to erupt with great violence. Another fact that was brought out by this study. Of the 80 largest explosive eruptions since 1750, 19 came from volcanoes which had been considered extinct!

Here is the dilemma that the volcanologist is faced with. The volcanoes that present the greatest hazard are precisely those that erupt least often. We have the least amount of data on them because they are rarely monitored. So the question is: How does one cope with this problem? As I pointed out earlier, the only way we can approach a volcano like this is to study its geologic record as Christiansen has done at Shasta and Lassen. It would be hard to find a better example of a very thorough study of a volcano than that of Mt. Shasta. This volcano is in the middle group which has had fairly recent eruptions but nothing in historic time. All its characteristics are of a dormant volcano that could erupt explosively near a populated area.

As in virtually all research studies, the data a geologist collects will never be complete, and he must take pains to avoid a biased record of the volcano's eruptive history. This can happen very easily if sampling is incomplete. The products of the most explosive eruptions are much more readily lost to erosion. Very explosive eruptions tend to be of siliceous, silica-rich magmas, and they are frequently very pumiceous with much fine debris that is carried off by the first rainfall. Of course, one can find deposits of this sort of material in lakebeds and bogs, and Don Mullineaux has demonstrated that one can, in fact, put together what seem to be very complete records of past eruptions from a diligent search for these deposits.

I often think of a volcano that I was personally familiar with in Nicaragua, Coseguina, which erupted in 1835. It is said to have been one of the greatest explosions in recorded history. (To give you an idea of how terrifying it was, there is a record in a Church in the Province of Olancho in northern Honduras that said that the terror of the inhabitants of this province was so great that 360 couples living out of wedlock rushed to the Church to be married.) When the volcano erupted, it covered most of Central America with a heavy layer of pumice. If you go there today and search for this pumice, you will be hard put to find any trace of it. It was washed off into the sea and there is little record that this great eruption took place only a century and a half ago.

A word about the matter of patterns or cycles of activity -- we all instinctively look for patterns and tend to place a great deal of weight on them. They certainly must be taken into account when dealing with volcanoes. Certain volcanoes tend to erupt with a particular frequency, and every few hundred years or so there may be a large explosive eruption. Part of the geologist's job is to find what the spacing of these eruptions has been, and from this, anticipate the next one. There are two problems with this approach. We are in the position of the meteorologist who may say, "In this particular zone, we are likely to get a certain number of snowfalls each winter." But, if he is trying to predict whether it will snow tomorrow, it makes a lot of difference whether it is July or December. So, in working out a cycle, it doesn't take a great deal of wisdom to say that within the next century "x" volcanoes are going to erupt. That may be of interest, but what you really want to know is where are we in the cycle and how close are we to the next eruption.

Another technique is that of using statistics on the frequency of activity in particular groups of volcanoes. Let me describe an example that I am personally familiar with. I had the opportunity a few years ago to review plans for a very sensitive industrial installation that was being built at the foot of a volcano that may or may not be extinct. This study was probably the most thorough investigation of a long-dormant or long-inactive volcano ever performed. The cost and the amount of data that were involved were staggering. Everything conceivable was done, but, in the end, we came down to the point where we had to answer two simple questions: 1) Is

this volcano going to erupt or isn't it? and 2) If it erupts, what is it going to do to this industrial installation? In the end, we were at a loss as to what to say.

Now it turns out that engineers, in particular where legal problems are involved, require a numerical estimate of the probabilities of risks. They want to know, for example, whether there is one chance in a million that the project would be endangered by an eruption. In this particular case, the probabilities were arrived at in the following way: First, in the course of studying the volcano, almost every piece of solid rock that was recovered from the slope of the volcano was analyzed, and if it was datable, its age was determined by the Potassium-Argon method. An extraordinary number of chemical analyses and Potassium-Argon dates were obtained and the ages were used to calculate a statistical frequency of eruption for the volcano. In the end, this method yielded a figure of one eruption per four-thousand years with the last eruption having taken place some 50,000 to 60,000 years ago. So, it was concluded that the volcano had outlived its active cycle and was no longer a serious hazard.

In essence, the geochronological study was based on dating of lava flows. Since the volcano is in a tropical environment where outcrops consist mainly of deeply weathered lava flows, lava flows were all that could be dated. The dating showed how frequently the volcano had erupted lava and was largely irrelevant to the problem. This is like a patient asking his doctor if he is going to die of a heart attack and, in turn, being asked how many colds he has had in the last ten years. There is just no correlation between the data and the prediction.

Another approach used in this was was to consider the frequency of catastrophic eruptions from volcanoes in the same region. By looking at the number of very large explosive eruptions that have occurred during the period for which good records are available and dividing this number by the number of volcanoes and the number of years of the record, one can come up with a frequency of large eruptions per volcano in that region. This was done by two different persons using two different sets of data, and as you might expect, the results were wildly different. One gave a figure of one eruption per 5,319 years and the other one eruption per 420 years. Thus, the estimated probabilities of a major eruption in this region differed by an order of magnitude.

Again, we can use the analogy of the patient and his physician. If you ask your doctor the same question, am I going to die of a heart attack, it is no help to you for him to tell you that of men in your age group so many die per year of heart attacks. That may be of interest but it is not what you want to know. You want to know whether you are going to die of a heart attack.

So the question is: How can we deal with each individual volcano in its own right? I don't think that we have the answer yet, although we may be approaching it.

In summary, the following points are worth reiterating. First, it's not just eruptions that we are anxious to predict; it's catastrophic eruptions. There is an important difference between an eruption and a volcanic hazard. Second, the volcanoes that present the greatest hazard to us and are most likely to be devastating in costs and lives, are those that are most difficult to study, and are least likely to be monitored. And finally, the only way that we can hope to understand volcanoes and accurately predict their activity is through research on the basic mechanisms of volcanism. The sad fact of the matter is, we simply do not know why volcanoes erupt and cannot explain why one volcano behaves so differently from its neighbor. Until we can answer these questions, most of what we do will depend on empirical observations, rules of thumb, and simply doing what proved to be useful in the past.

DISCUSSION

Question: As a layman, I wonder if there is one major item of interest as a result of Mount St. Helens that would change your preconceived ideas about geologic hazards work?

McBirney: I would say that it taught me that the biggest problems are political and economical, not geological. The geologist is in a position where he is expected to make specific predictions far beyond his ability. I also learned that it is very difficult to conceive of the magnitude of major eruption unless you have seen the power of something like Mount St. Helens.

On the positive side, I learned that the U.S. Geological Survey was able to come in quickly and set up an exceedingly efficient monitoring system. Certainly this was the most all-out effort of its kind that has ever been mounted. As a result, we will end up with what will certainly be the most detailed, most precise record of a major volcanic eruption that we have ever obtained. We will be using the data obtained from this eruption for many years to come.

Question: You have described the problem of infrequent, but hazardous, eruptions. So, how do we attack that? Do we have very limited or marginal monitoring, very simple devices, one tiltmeter per volcano or per cinder cone or whatever, or do we just take blind stabs at places that might be dangerous? What is the monitoring approach?

McBirney: I guess someone like Roy Bailey should answer that question. But in general, there are always premonitory phenomena that precede a large eruption, and it is unlikely that such an eruption would occur unannounced. Earthquakes would be detected or you would notice some thermal phenomena that would draw attention to that particular volcano. Then we could move in and begin to monitor the volcano more closely.

Question: Looking back at the records prior to the eruption of Mount St. Helens, are there detectible phenomena which could have been associated with the premonitory events dating back weeks or months? I am not talking about March 27, but the periods of months or years prior to that. Do you see anything in the seismic or magnetic or other phenomena that you studied?

McBirney: I think that Steve Malone is going to tell us about the seismic record, but there were, of course, earthquakes even before the earliest eruption. I think if you go back and look at the bulletin put out by the U.S. Geological Survey on the volcanic hazards of Mount St. Helens, you will see that the hazard was clearly defined, and this drew attention to the volcano, so that people were watching it more closely. Even before the eruption, it was commonly said that, of all the volcanoes in the Cascades, Mount St. Helens was the one that should be watched more closely. In terms of what we might have looked for, apart from a few earthquakes, I am not aware of anything else that could have been done. Rick Kienle, are you aware of anything that would have tipped us off as to something that was coming?

Kienle: Crandell and Mullineaux's studies of the volcano pretty well established the pattern.

McBirney: Of course, the initial eruptions were phreatic and were really not much cause for concern. It wasn't until the bulge started that we had reason to worry.

Question: When you talk about a range in intensities, as well as catastrophic events, where do you place Mount St. Helens?

McBirney: If you mean in terms of total destruction you would have to take into account the mudflows and all of the effects down the Toutle and Cowlitz rivers. In terms of the magnitude of the explosion, it was well into the upper ranges, and it would fall in that group of volcanoes with repose times of the order of centuries -- which is, in fact, about the periodicity of previous intervals between major eruptions. I might add that Mount St. Helens has had eruptions that were even bigger than the last one. So in that sense, the explosivity was probably medium to high in qualitative terms.

Question: Do you feel that Mount St. Helens might be somewhat of a geologic accident

and in a similar situation with the same amount of juvenile material, it would not have resulted in an eruption as destructive?

McBirney: If the eruption had been directed vertically, yes, it would have been a very different matter. In that sense, I agree. We should bear in mind that the eruption was highly unusual, almost unique. This phenomenon of a slope failure triggering a hydrothermal eruption that was followed immediately by a large, magmatic eruption is quite unusual. It is hard to put the Mount St. Helens eruption into any category except one that is all by itself.

Question: In the concept of plate tectonics, how do we explain the Cascades as a volcanic chain being so stationary for such a long period of time?

McBirney: In fact, it isn't such a long time. That is one of the dilemmas. The Cascade Range that we are looking at today is a product of the last million years. The cones that are so large and imposing have grown over a very short period of geologic time. If you look at Cenozoic time as a whole, you will find that in the past we have not had this long chain of big composite cones but a wide variety of conditions. If you had a time machine and picked a time at random to go back and examine the Cascades, let's say sometime in the last 40 million years, the chances are that you would arrive at a time when nothing was going on. The whole region would be quiet, and you would not see a long chain of volcanoes, although you might see a lot of small scattered vents. The types of activity have changed from period to period, and the locus of activity has shifted back and forth. The simplistic picture that we have of a plate going down beneath the North American Continent and a line of volcanoes back a certain distance from the trench fits the present-day conditions admirably well, but if you go back into time, you see that it does not fit at all. It is a real problem to reconcile this strongly episodic and varied activity with a process of subduction that is supposed to be a steady one. That's no answer to your question, I realize.

Question: In the old days, they used to talk of a wave of volcanism that moved from the West Coast through the Basin and Range transgressing eastward. Have we lost that concept in our geologic reasoning?

McBirney: I think that was a bit of an oversimplification. If you look at the Cascades as a whole, let's say you start with the earliest orogenic rocks that we can associate with subduction, possibly in Eocene time, the vents were scattered all over the Northwest. They covered central Oregon as far east as Idaho. There is then a gap in the record until Oligocene to early Miocene time when another group of big volcanoes was situated in the general region of the central Cascades but were broadly scattered. So the focus seemed to have moved somewhat westward in that case. The next episode in the mid-Miocene, was down the axis of the western Cascades. It lies west of the High Cascades in the south and east of the High Cascades in the northern part of the chain. So it has actually rotated clockwise with respect to the present axis. Pliocene volcanic rocks are scattered all over central Oregon. So there is no clear pattern, or if there is one, I haven't discerned it.

Bailey: I just wanted to comment on your suggestion for support for basic fundamental research in an attempt to understand the periodicity of explosive volcanoes. This is a problem from a budget standpoint. If you get a budget cut, that is the first thing they want to get rid of -- basic research.

McBirney: I share your feeling because I am vulnerable too, Roy. That's why I put in that plug! I think we have to emphasize that our understanding of volcanism is inadequate. I have used the analogy of the physician or medical profession, which I think is a good one. We are even worse off than the doctors. They may not know what they are doing either, but they at least put up a better front than we do. We can't even agree among ourselves what the cause of an eruption is. I may think I understand what is going on, but I am sure you have a different view, as does everyone else. So the only

way we are going to resolve this is by getting down to fundamental processes and understanding what is going on underneath the volcano. Ray Wilcox once used an analogy which I thought was very apt. He said studying a volcano by looking at it from the surface is like looking at a factory where all you see is the smoke coming out of the chimney and the product rolling off the assembly line, and trying to guess what is going on inside the building. What we have to do is go back to old deeply eroded and dissected volcanoes, just as one makes an autopsy on a corpse, and try to decide what it was that did it in. It takes a lot of hard geological and theoretical work to put this together.

REFERENCES

Bailey, Roy A., 1982, Potential Eruption Centers in California: The Long Valley-Mono, Coso, and Clear Lake Volcanic Fields, in this volume.

Christiansen, R.L., 1982, Volcanic hazards in the California Cascades: Shasta, Medicine Lake, and Lassen volcanoes, in this volume.

Crandell, D.R. and Mullineaux, D.R, 1978, Potential Hazards from future eruptions of Mount St. Helens volcano, Washington. U.S. Geological Survey Bulletin 1383-C, 26 p.

Kienle, Rick, 1982, Impacts of the Mount St. Helens eruption on industry, in this volume.

Mullineaux, D.R., Hyde, J.H., and Rubin, Meyer, 1975, Widespread late glacial and post-glacial tephra deposits from Mount St. Helens volcano, Washington: U.S. Geological Survey Journal Research, v. 3, no. 3, p. 329-335.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J.H., 1981, Volcanoes of the World: Academic Press, New York, 233 p.

Walker, G.P.L., 1974, Volcanic hazards and the prediction of volcanic eruptions: Geological Society of London Miscellaneous Publications, v. 3, p. 23-41.

THE MOUNT ST. HELENS ERUPTIONS: SEISMIC MONITORING FOR ERUPTION PREDICTION

Steve Malone
Geophysics Program AK-50
University of Washington
Seattle, Washington

ABSTRACT

On March 20, 1980, an unusual earthquake sequence began with a single magnitude 4 earthquake beneath Mount St. Helens. This earthquake sequence rapidly progressed to the point where on March 25, during one eight-hour period, 24 magnitude 4 quakes occurred beneath the volcano. Small steam and ash eruptions began from the summit on March 27 and continued intermittently along with strong earthquake activity for the next 7 weeks. The number of large magnitude events and the concentration of epicenters beneath a region of high deformation on the north flank of the volcano probably represented the injection of magma into a shallow reservoir. There were no unusual changes in the seismic activity in the hours preceding the cataclysmic eruption of May 18. This eruption began with a magnitude 5.1 earthquake, which triggered the slope failure of a large part of the north flank of the mountain. This, in turn, triggered a large laterally directed eruption which devastated over 500 square kilometers of land.

There have been nine subsequent eruptions which have had recognizable seismic precursors. The first of these on May 25 occurred at 0232 PDT after a three-hour hiatus in the harmonic tremor amplitude. On June 12 increasing harmonic tremor was observed 9 hours before the eruption. This harmonic tremor had its major pulse at 2111 PDT, but an unusual earthquake sequence with increasing numbers of shallow events was recognized eight hours earlier. On August 7, again harmonic tremor was recognized as a precursor starting four and a half hours before the 1630 PDT eruption. On October 16 shallow volcanic earthquakes preceded a major ash eruption by about 30 hours. From December 28 to January 4, 1981, from February 5 to February 8, from April 10 to 12, from June 18 to 20, and September 5 to 9, major dome growth took place in the crater. Each of these non-explosive eruptions was preceded by an intense earthquake sequence.

Precursors to all of the eruptions, with the exception of the cataclysmic eruption of May 18, 1980 and May 25, 1980, were recognized at the time and warnings were issued to civil authorities.

INTRODUCTION

There appears to be two classes or types of predictions: the probabilistic or stochastic type of prediction and the deterministic one. The probabilistic is based on what happened in the past. The historical record or geologic record is used, along with the fundamental assumption that the future will be, at least statistically, similar to the past, to predict future behavior. For earthquake prediction this is probably the most common type, rather than the deterministic prediction in which you specify in more precise terms what size event is going to occur and when. For volcanic eruption prediction one can look at the record or the history (in some parts of the world it's much longer than in the U.S.) and try to draw some inferences as to the probability of a certain

mountain or certain mountain range having an eruption in the foreseeable future. As Dr. McBirney (this volume) pointed out, maybe that is not the really important thing because your real interest is the hazards from eruptions. A probabilistic prediction should, however, influence long-range planning, where to build the large engineering structure, or how to build it to withstand whatever occurrence may take place. At Mount St. Helens, the Crandell-Mullineaux (1978) hazards report is a good example of what might be called a successful probabilistic prediction. They said, based on the historical and geological record, that Mount St. Helens would likely erupt within the next few decades, perhaps by the end of this century. They were right.

On the other hand, work on deterministic predictions is probably what is going on right now at Mount St. Helens, where we use the here-and-now monitoring to predict what is going to happen tomorrow. In a sense the difference between these two is just a matter of time-scale. There is obvious overlap, but there are some fundamental differences in the type of data that go into them and the type of policy that they affect. In fact, today's papers are divided along these two lines: those this morning, which deal with the geologic character of volcanoes (giving rise to probabilistic inferences); and those this afternoon, which deal more with instrumental methods of surveillance or monitoring and which look for short-term precursors useful for deterministic predictions. The time-scales for deterministic prediction may be hours to weeks while the probabilistic ones are of many years to decades and even centuries.

VOLCANO SEISMOLOGY

Seismology is not at all useful for the probabilistic or long-term type of prediction in the case of volcanoes. The geologists do a lot better job. In the short term, however, I think it is perhaps the most important geophysical or geological tool. Maybe all of the rest of them put together aren't as important as seismology. Of course, I'm a seismologist and in these budget-cutting times you'll forgive me if I do a little self-serving advertising here. I hope to show that in the case of at least the Cascade Range, and maybe all of California, under the situation that we are in right now, seismology is by far the most powerful tool to use initially.

There are several lines of reasoning to support the importance of seismology. The type of volcano that Dr. McBirney mentioned as being a rather rare erupter is certainly not going to have a very open type of vent system. For the magma to reach the surface, it will be necessary to break rock. It will increase the stresses in the earth enough to fracture rock to allow a path to the surface. The fracturing of the rock results in earthquakes. Just as, if you break a stick, it goes snap, when the rock fractures, it radiates vibratory energy, and is recorded by the seismologist as an earthquake. I think it is pretty fair to say that any time there is magma moving at any significant volume or speed, earthquakes will be generated. A study by one of Dr. Decker's former students (Unger, 1974) examined some 70 or 80 volcanic eruptions for which seismic monitoring was available. Of those, there were no more than two or three without precursor earthquakes, and in those cases the eruptions weren't particularly violent. On the other hand, a third of the volcano-associated earthquake sequences studied did not eventually end up in eruptive activity.

Another plug for seismology is that there are a lot of seismologists and seismic equipment around already. For years, earthquakes have been studied for their own sake. Various types of seismological exploration and research activities have poured quite a bit of scientific expertise, not to mention money, into seismology. Hence, we are already well prepared to use seismology for looking at volcanoes.

Generally speaking, seismic waves propagate quite efficiently in the earth's crust. Seismic surface waves weaken with distance from the source at one over the square root of distance. Many of the other types of monitoring techniques such as deformation or strain drop off much more rapidly, meaning you must have your sensors much closer to the source, or they must be quite a

bit more sensitive,to get the same type of detection threshold. Existing seismic networks in California are probably capable of detecting any preeruption earthquake activity in the state.

SEISMIC MONITORING AT MOUNT ST. HELENS

From a seismologist's point of view, in the period prior to March 27, seismology was the whole story at Mount St. Helens. We consider March 20, 1980 to be the beginning. In looking back at the seismic data from before March 20, we recognize a small increase in microearthquake activity that started about the 16th, four days earlier. It was the type of increase that, unless one were carefully watching for it, it could not have been recognized, and it wasn't. It was March 20 that we noticed Mount St. Helens as being a bit unusual, and that was because of the $M_L = 4$ earthquake which occurred that Thursday afternoon about 3:47. Within an hour, we had located it virtually under the summit of the mountain at what appeared to be a fairly shallow depth. At the time there was only one seismic station within 50 km of the mountain, yet this event was recorded over most of the state. Even with this very sketchy type of network, our epicenter location turned out to be within just a couple of kilometers from where all the subsequent activity was located. This is an example of how a seismic network can be quite useful, even a fairly sparse one. At this time, we didn't think that a volcanic type of event was necessarily occurring. While it was the largest event at Mount St. Helens since the western Washington network had been expanded into the Mount St. Helens area in 1972, it was not as big as the M = 5 earthquake that occurred on the flanks of Mt. Rainier a few years before. That event did not signify any unusual volcanic activity at Rainier.

We decided to install some additional equipment on Mount St. Helens in case there were aftershocks. In just a little over twenty-four hours, we had established three additional local recording stations near the mountain and an additional telemetry instrument at some 30 km distance. The local recording stations were recording on magnetic tape, and thus, were not very useful for immediate analysis. The telemetry stations were of immediate use because they record back in our offices in real time. There was, over the next several days, additional activity occurring which was not quite like an aftershock sequence.

Figure 1 shows a helicorder record from the telemetry station located on the flanks of the mountain about 3.5 km from the summit. It shows the two days from Friday night, March 21, through Sunday night, March 23. Note the increase in activity about half way through this period. Saturday night, March 22, we started thinking that this was not very typical, and Craig Weaver contacted the Forest Service. I ended up talking with their avalanche forecastor because the earthquakes were triggering snowslides. The Forest Service people decided they would close the upper part of the mountain because of avalanche hazard on the following day, Sunday. On Sunday, I again talked with their avalanche forecaster and first mentioned the possibility of volcanic activity. In retrospect, we probably should have done it sooner. In a situation like this, it is difficult to believe what is going on right before your eyes. It was a first-time experience for all of us.

The Forest Service was sufficiently concerned that by Sunday night or Monday morning they called the U.S. Geological Survey volcanic hazards group in Denver. I did too. I explained to Rocky Crandell that I didn't know what was going on, but it surely was weird, and we needed help. Tuesday night, Don Mullineaux was in Vancouver, Washington where the Forest Service headquarters are. He sort of rescued us from the press and concerned officials. We could point at him to tell us what was going to happen, having had more experience with this type of thing. Monday, March 24, Dave Frank, a geologist, went up in an airplane to take a look at the mountain, and noticed nothing unusual. The geologists weren't convinced, but back in the lab the seismologists were both confused and concerned. The rate of seismic activity increased to the point that on Monday night one could not distinquish one event from another on the seismograms of the nearby

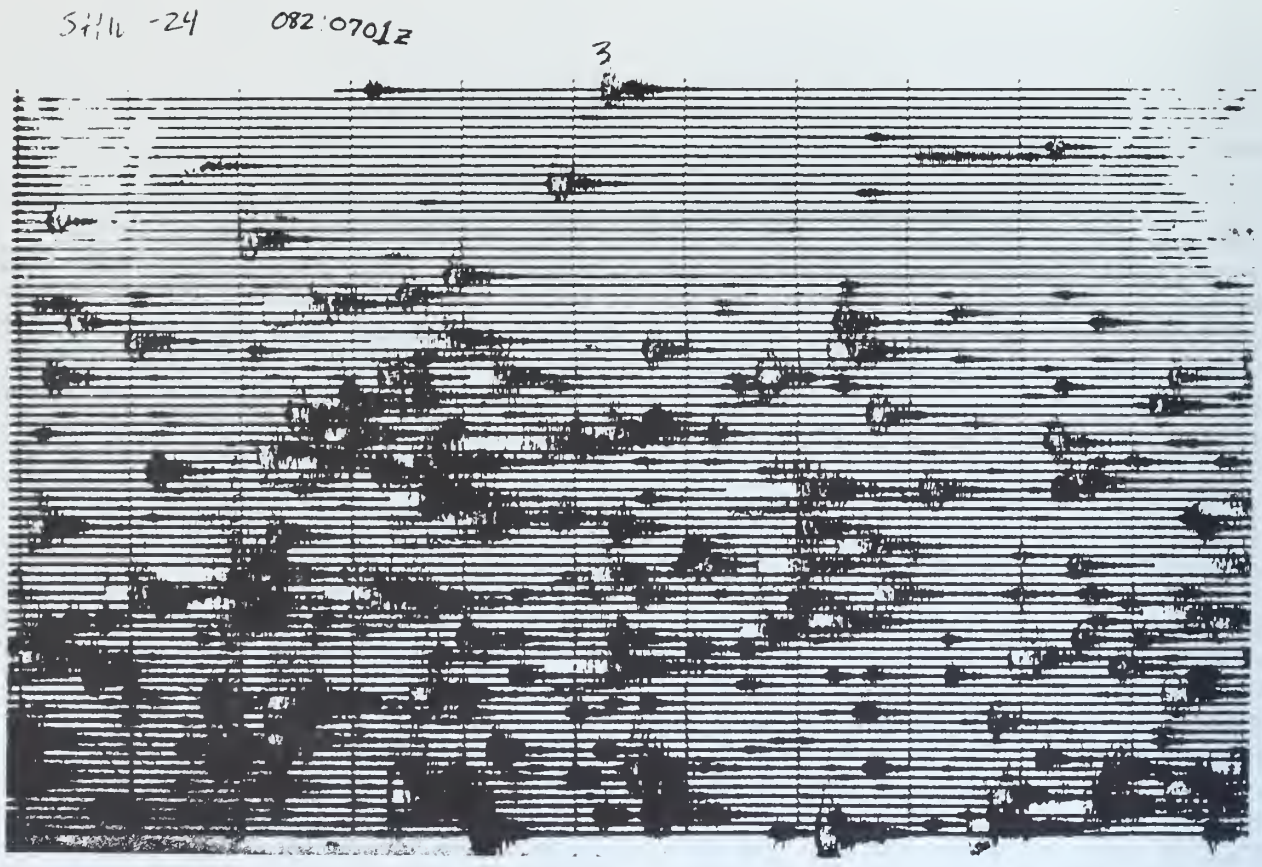


Figure 1. Increasing seismic activity between evening of March 21 (top of figure) and March 23 (bottom).

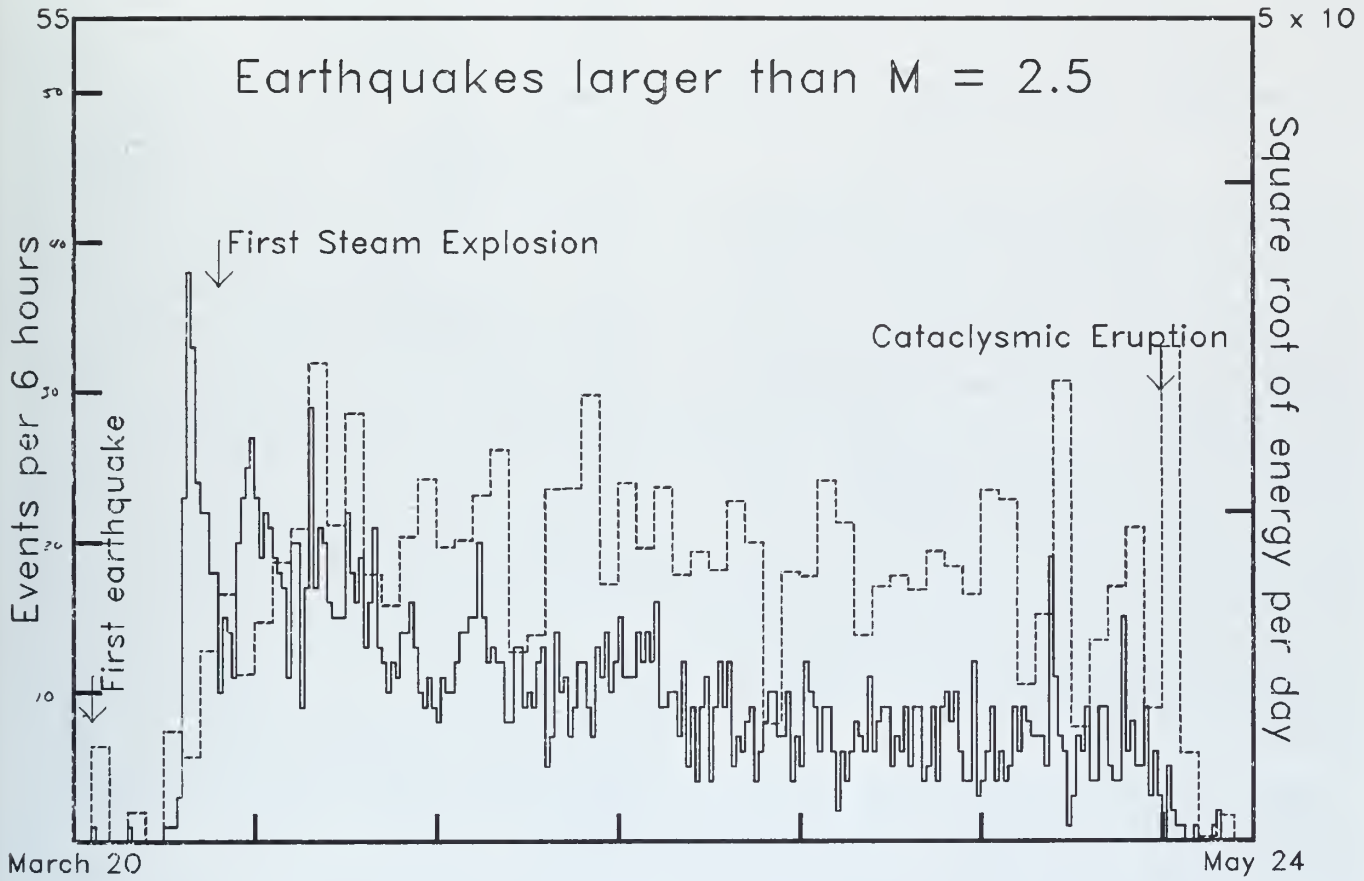


Figure 2. Counts of earthquakes larger than magnitude 2.5 are shown by solid line, and energy release by dashed line. As frequency of earthquakes declined, average magnitude increased, as shown by nearly equal energy release during the period.

station. Rather than monitoring the station on the mountain, we switched to a station that was 112 km away. Even at that distance signals were very obvious, and one would have had to have been a fool not to have noticed that something unusual was taking place. Tuesday night Don Mullineaux issued a statement that said something to the effect that "an eruption in the near future of Mount St. Helens is a distinct possibility." Wednesday, the activity died down a bit, and we thought it might be over. Thursday, March 27, a hole blew open in the top of the volcano convincing everyone it was a real live volcano.

Phreatic eruptions and strong seismic activity continued for the next two months. The seismic activity over these two months is shown in Figure 2. The number of events per six-hour period is plotted in solid black versus time over roughly the two-month period, starting back in March 1980 through the eruption on May 18. The activity peaked early in the sequence, then declined almost like an aftershock sequence. On the other hand, the daily seismic energy content did not decline because, while there were fewer events near the end of the sequence, the average event was becoming larger. There were obvious geodetic changes that took place during this time, most notable of which was the bulge growing along the north side of the volcano.

Before going any further with the seismology story, it will be useful to look briefly at what makes up a seismic system or network. It starts with a seismometer, which is a small device about the size of a beer can, placed in a shallow hole. This sensor is simply a transducer which produces a small electrical current in response to vibrational motion. That current then is sent via cables to battery-powered equipment which amplifies that signal and converts it into a form which can be easily telemetered. Around Mount St. Helens, it is transmitted by radio out to where there are telephone systems. The signals are sent to the University where there are electronic gizmos that discriminate these signals and record them in a variety of ways. A helicorder produced the record shown in Figure 1. It is a drum that slowly turns with paper on it. As the ground shakes at the remote site, the needle in the helicorder traces back and forth writing a record. We also have develocorders, a film type of recorder, probably the most common type of recorder, at least, in this country. On these devices 16 channels can be simultaneously recorded on microfilm, and viewed through a special viewer. Certain aspects of the wave train, as it arrives, can be identified for the purpose of locating and studying the earthquakes. At some institutions lucky enough to have more modern equipment, computers listen to all channels of seismic data, digitize, and record them on magnetic tape. It is event-triggered so that it only records if the computer thinks that an earthquake is in progress. There is a delay line so that information before the time of the event can be saved. We also have a fancier computer that allows one to display the seismic traces on graphics terminals, among other things. These traces can be displayed in many different ways by filtering them and expanding the scale so that one can see essentially every gruesome wiggle. Figure 3 shows all the seismic stations in our network operating at the end of 1980 in the State of Washington. We have recently expanded the network into the northern part of Oregon and now are capable of detecting earthquakes down to magnitude 2 over this entire area. In the Mount St. Helens area, we not only detect, but locate earthquakes down to about magnitude 0. Zeroing in on the Mount St. Helens area, we see in Figure 4 the network essentially as it is running now. The triangles are currently operating stations. The station labeled SHW has been operating since 1972. The round dots are temporary stations that were put into the area shortly after the initial earthquake sequence. In fact, within ten days, we had ten stations operating within a 30 km radius of the mountain.

One of the major problems of using seismology as a predictive tool is discriminating between events due to normal tectonic processes from those due to the migration of magma. For an example, Figure 5 shows two kinds of earthquakes. On the left is a low-frequency earthquake in which the frequency of the trace motion is lower than the one on the right side. It typically has

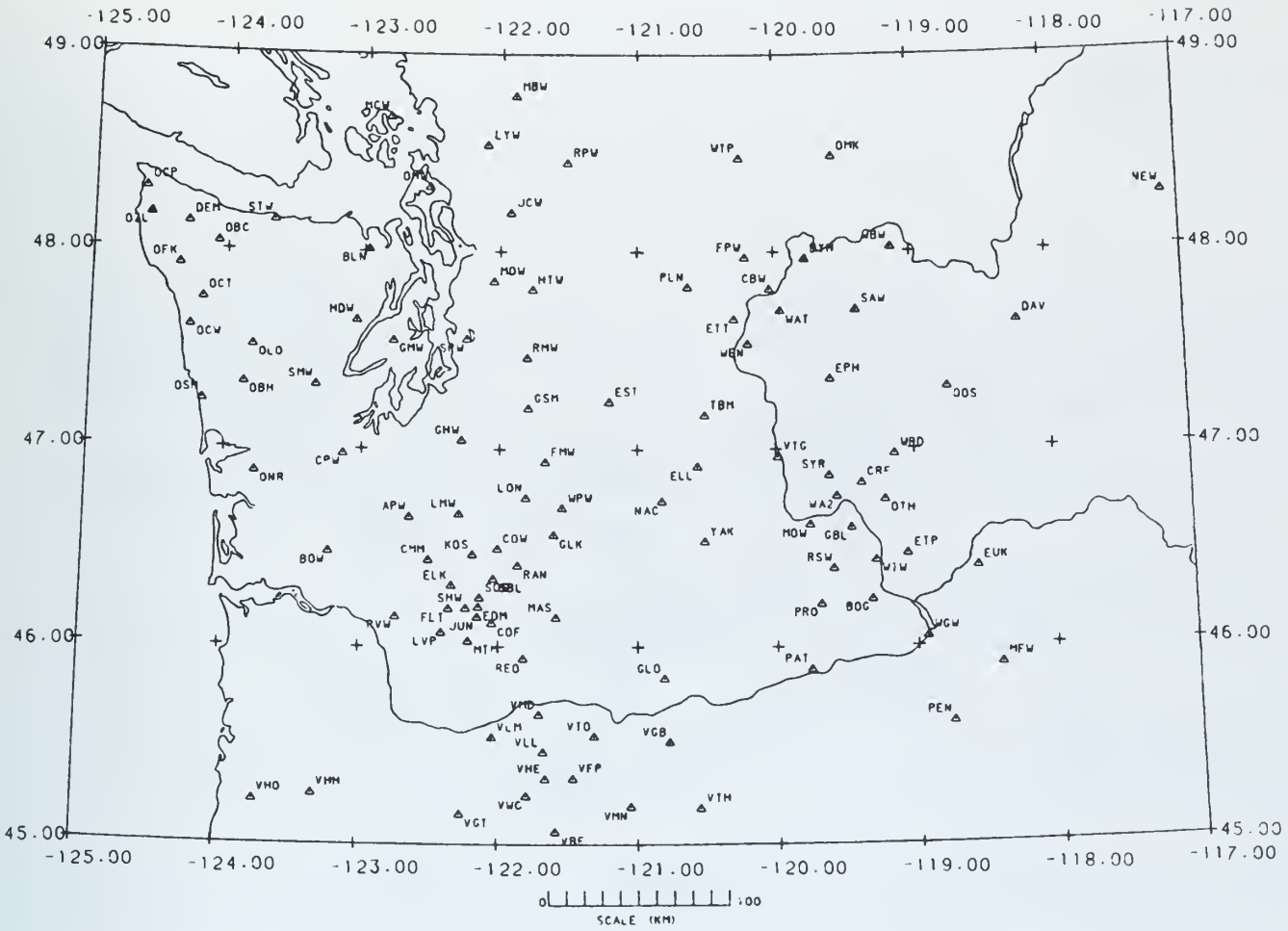


Figure 3. Seismic stations of the University of Washington operating at the end of 1980.

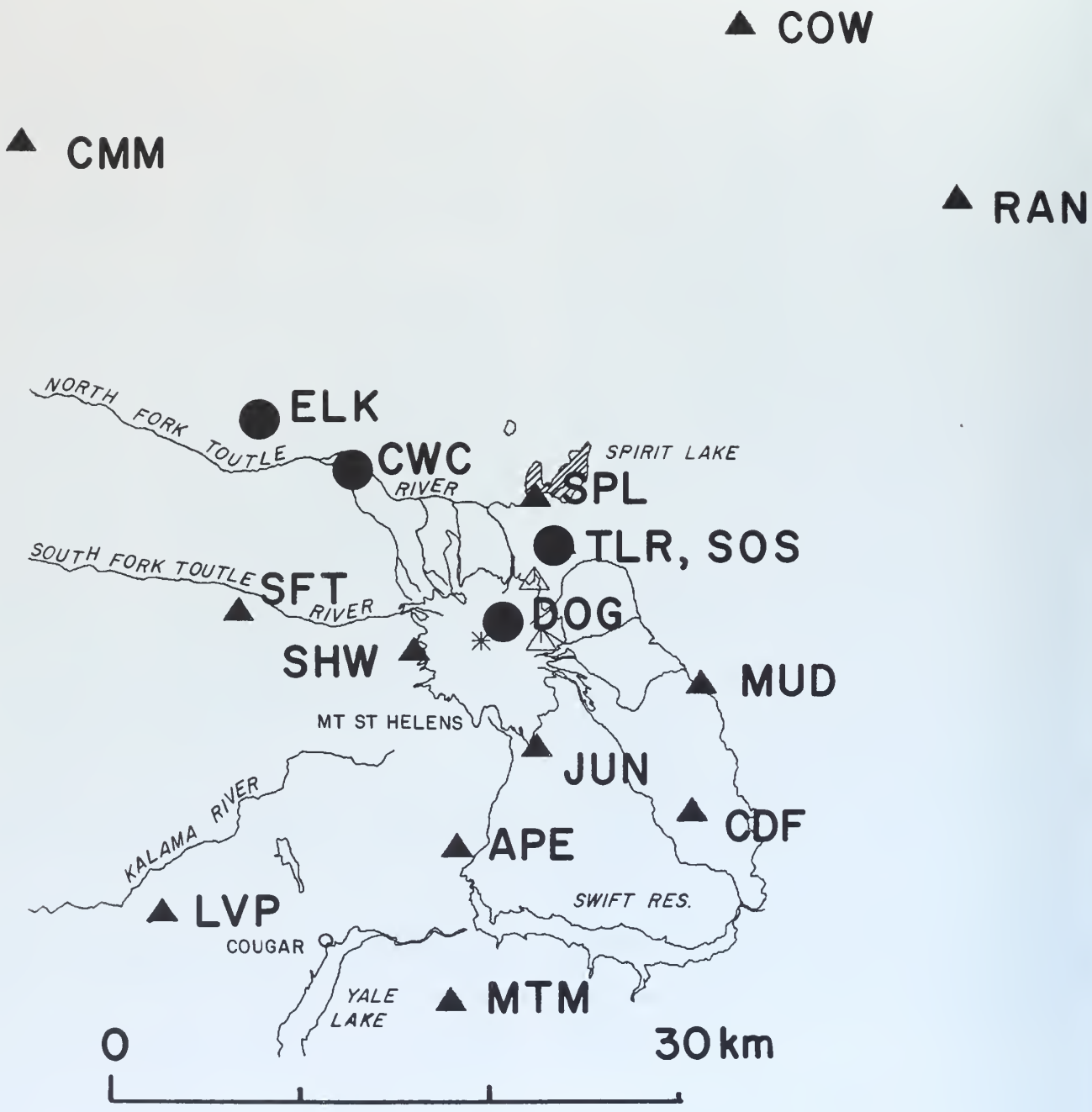


Figure 4. Currently operating seismic stations of the University of Washington at Mount St. Helens are shown by triangles. Dots show temporary stations set up early in the seismic sequence.

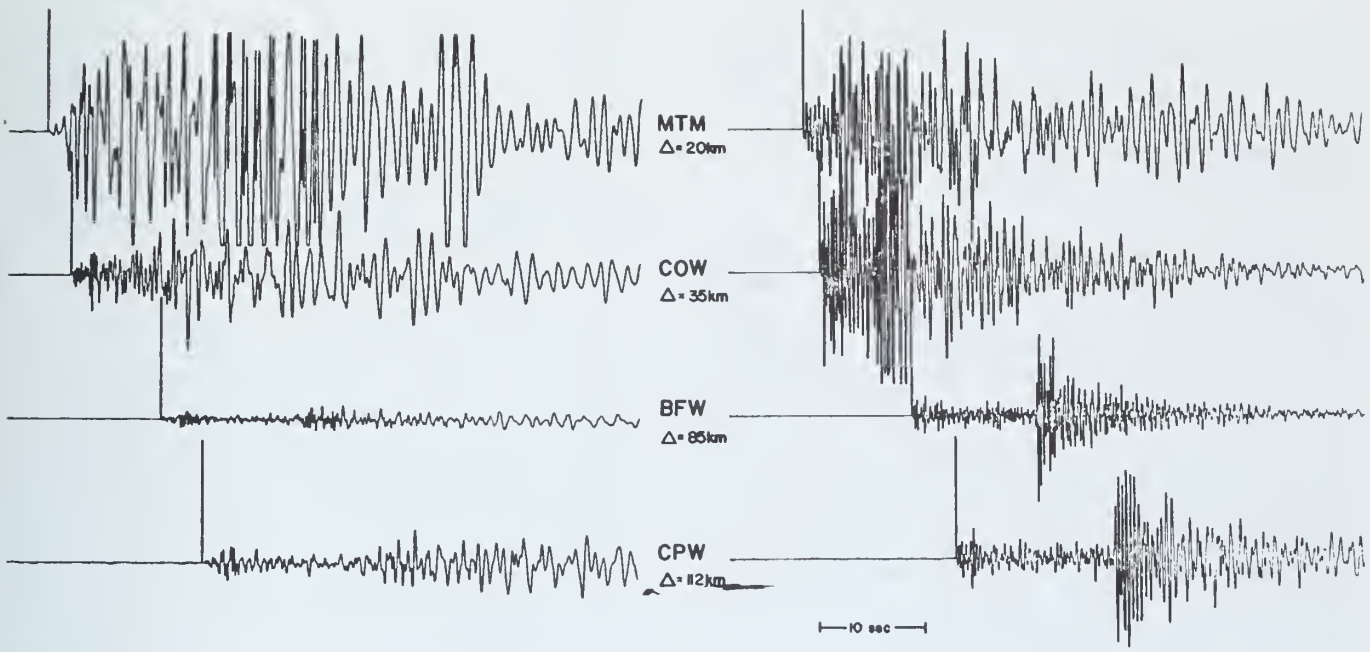


Figure 5. Signatures of a low-frequency (left) and a higher-frequency (right) earthquake as recorded by four seismometers in southwestern Washington.

less distinct phases and a long monochromatic coda (single-frequency signal). On the right is a typical higher frequency earthquake with better defined phases. The reason for the differences between these is not particularly well understood. There are two basic philosophies: one, that it is a source phenomena; there is something fundamental at the source that generates a different pattern. The other opinion is that it is a source location phenomena in which the propagation of the waves through the earth gives rise to these differences. Personally, I'm leaning toward the latter camp. I think it is due mostly to a propagation phenomena, but ultimately it will probably end up that it's partially both. This is an example of where a good deal of research in seismology applied to volcanoes needs to be done -- discriminating the difference between volcanic events and tectonic events.

Figure 6 is an example of what is called a B-value plot or a recurrence curve in which we plot the number of earthquakes larger than a certain magnitude versus magnitude. The difference between the high-frequency or more tectonic-like events and the low-frequency or volcanic events is indicated. The high-frequency events have a lower slope, typically about one, and the low-frequency events have a slope greater than two and one-half. This has been observed all over the world in volcanic regions where the stress field and/or the medium is highly heterogenous. It simply means that there are a lot more small events proportional to the number of large events in the volcanic areas.

There are other types of seismic events that occur on volcanoes. In fact, one is not really an event. It is something called harmonic tremor. An earthquake seismogram is compared with harmonic tremor in Figure 7 recorded at the same time-scale and at the same distance from the source. The difference between these records is really quite obvious. The earthquake is a transient event, and probably represents the fracture of rock that took place over a short interval of time. The seismic waves then radiate away from that source. Harmonic tremor, on the other hand, appears to be a continuous repeated source. The nature of that source is not well understood. There are a number of different models that might explain this type of signal, but there is not general agreement on any of them. There is pretty good agreement that it has to do with the transport of magma. During and before many eruptions, particularly in Hawaii, tremor is observed. It has been concluded that it is somehow related to the transport mechanism of magma. It may be purely a fluid type of generating mechanism, or it may be fracturing of rock. Small discreet repeated fracturing may generate tremor signals as a crack is expanded due to the injection of magma. There are a number of different models, and there are problems with all of them. Basic research needs to be done to try to define the particular mechanism. Nevertheless, harmonic tremor can and is often used as an indicator of fluid flow which may be a precursor to eruptions. In the case of Mount St. Helens, it certainly was in several instances.

Individual earthquake epicenters can be located precisely if you have a large seismic network. Figure 8 shows epicenters of some events which preceded May 18. They fall into a fairly tight cluster. This is only about 500 or 600 events out of several thousand that were recorded. We simply have not processed all the data yet. It is quite illustrative of probably what the rest of the events show, and that is that there is a very high concentration of events just north of the summit. Figure 9 is a cross section through the mountain. The earthquake hypocenters are tightly clustered at a very shallow depth under the north flank of the mountain. There are no events above average station elevation simply due to the mathematics of the location process. I think if we had an algorithm that could take care of this problem, we would probably locate events actually up within the edifice of the volcano. The unique thing is that the earthquakes were all shallow. There is almost nothing below 5 km, and the vast majority of events are within a couple of kilometers of our average station elevation, which is at roughly 1 km above sea level. These were the events before May 18, and, no doubt, represent the injection of magma into the base of the volcano. This eventually resulted in the eruption.

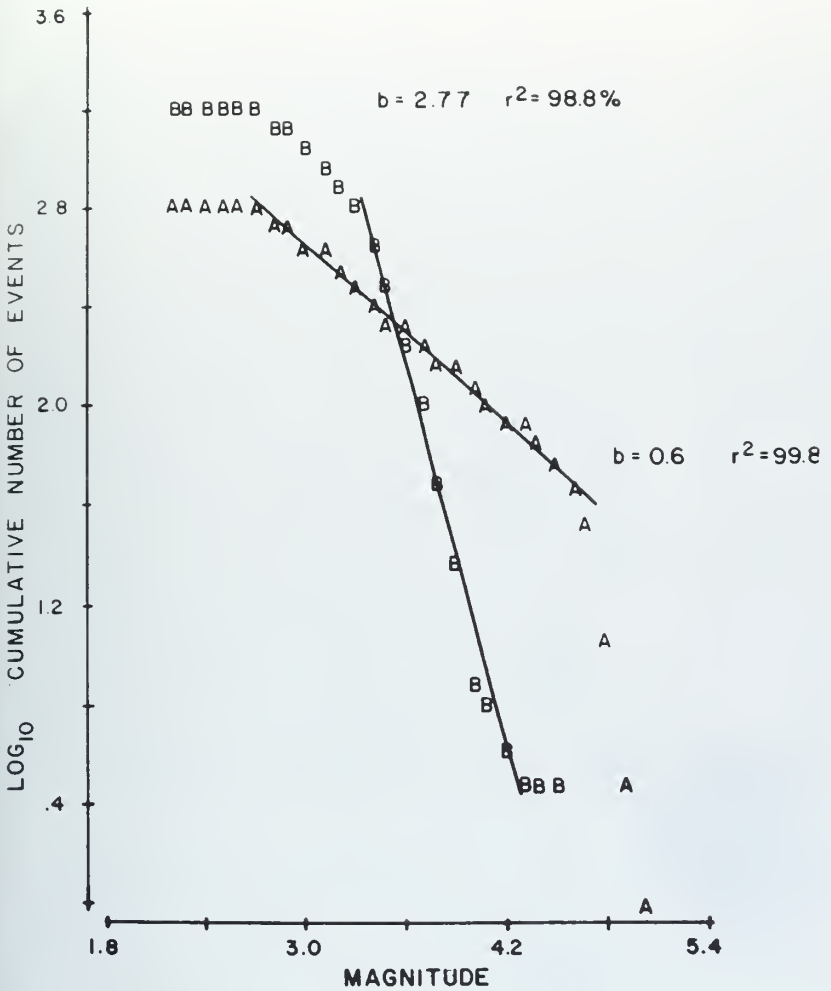


Figure 6. B-value plot of high frequency, tectonic-like events (A's) vs. low-frequency, volcanic event (B's).

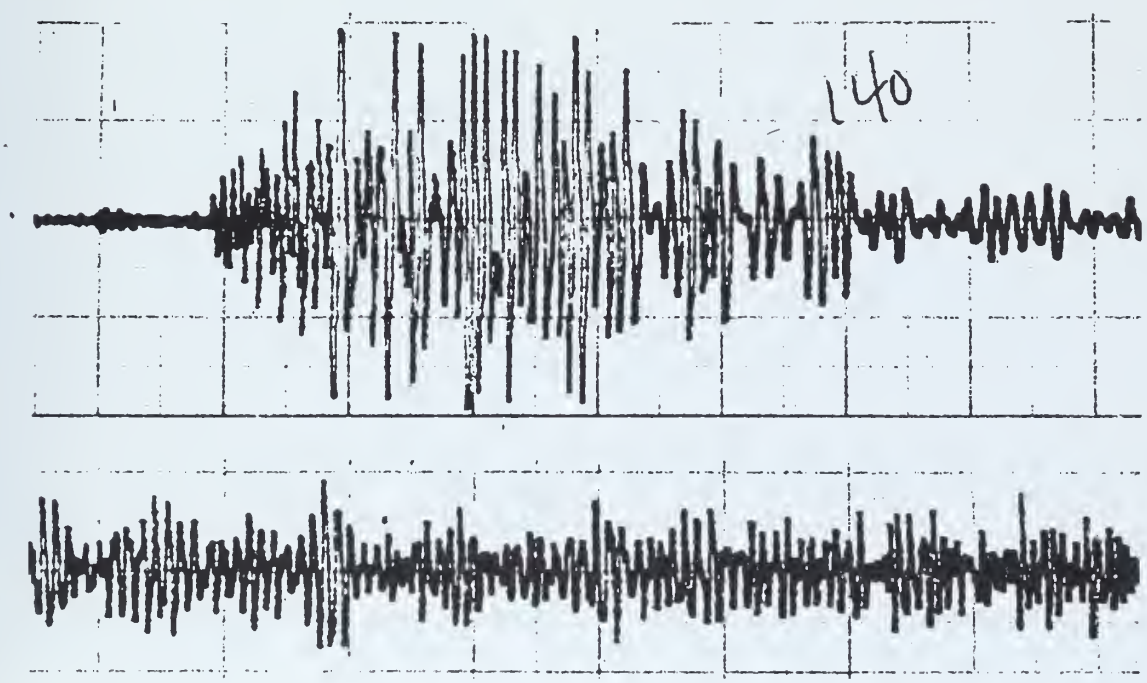


Figure 7. Typical earthquake seismogram (top) and harmonic tremor (bottom) as recorded at the same time-scale and distance from the source.

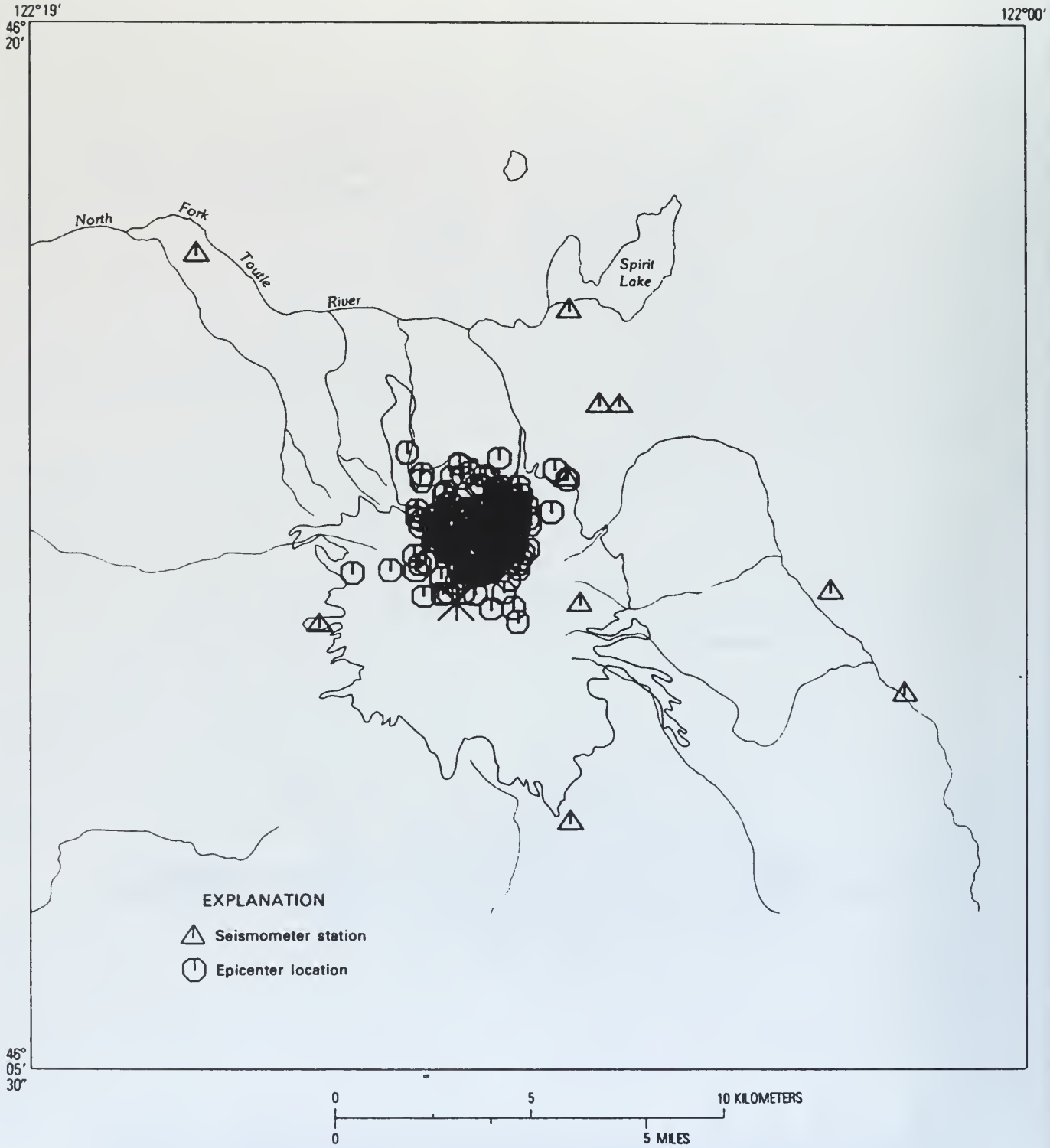


Figure 8. Plot of epicenters and seismic stations at Mount St. Helens occurring from March 27 to May 18. Figure from Endo and others (1981) U. S. Geological Survey Professional Paper 1250.

After the May 18 eruption, there was a change in the regional seismic pattern. Figure 10 shows epicenters for the time period after May 18 through the end of 1980. While the activity right at Mount St. Helens itself is certainly related to the volcano, there is other activity spread some 30 km north of the mountain, and 15 km or so south of it. It is hard to imagine that this activity is directly related to magma flow over that distance. The events to the north appear to have strike-slip mechanisms probably on a north-south trending fault or fault zone, with right lateral slip. Something changed in the stress field over a fairly large region at the time of the eruptive activity back in May, and that has actually extended into this year. Figure 11 extends these observations through the end of the summer, 1981. It includes a magnitude 5.5 earthquake that occurred in February. These are tectonic earthquakes, but their close relationship to the volcanic process at Mount St. Helens is obvious.

We turn now to some of the individual eruptions and, in particular, a look at the precursors to them at a time-scale that would allow one to run if you were nearby. For the May 18 eruption there wasn't a warning on that type of time-scale. There had been two months of very intensive earthquake activity, phreatic eruptions, and an expanding bulge on the north side with very high deformation rates. All of these are precursors, but it was not possible to use those data to predict exactly when that eruption would take place. I think there are some very good reasons why that was the case. The mountain really wasn't ready to erupt. We can blame it on an earthquake. There was an earthquake which triggered an avalanche on the north side. The avalanche, then, uncapped the hydromagma system, which then erupted. Since it wasn't ready, we would have had to predict the earthquake in order to predict the eruption. Science is further away from predicting earthquakes than from predicting volcanic eruptions.

For some of the subsequent eruptions, we were able to recognize seismic precursors. Figure 12 shows the seismicity associated with the May 18 eruption. Across the top, each vertical line represents an earthquake -- the height of the line is proportional to the size of the event. The dashed lines are the low-frequency earthquakes that I described earlier, and the solid lines represent the high-frequency ones. In this case, the mode of earthquake activity changed radically at the time of the eruption. The pre-eruption events were all very shallow, as you saw in the cross sections of Figure 9. The high frequency or tectonic events were deep -- down to 20 km. This is sort of an aftershock-like effect. Once the eruption got going, the shallow events ceased. Now there was an open vent, and material was coming out. It somehow changed the stress pattern all the way down to fairly great depths (20 km), and deep, high-frequency types of events occurred. On the bottom of Figure 12 harmonic tremor is plotted. It is hard to say whether it is truly harmonic tremor or not. The records are saturated with events and/or harmonic tremor. It is quite difficult to discriminate between the two. In the hours just before this eruption, there had been no harmonic tremor, though at isolated times in days before or weeks before there were periods of very strong harmonic tremor with no correlation whatsoever with anything occurring at the surface. It's postulated that this represented subsurface transport of magma which never erupted, at least, not at the time of the tremor. During the eruption, tremor may be generated by a different mechanism. Simple turbulence or the explosive action of the gas coming off would be enough to explain it.

For some subsequent eruptions the seismic data have been fairly successfully used for predicting within a few hours when it was going to occur. An example is shown in Figure 13 for the event on July 22. That morning low-frequency volcanic earthquakes, which had been virtually absent since May 18, began to occur. The mountain had not been active since June 12. The earthquakes increased in intensity and number over the afternoon of July 22. While we didn't predict the eruption to the hour, we expressed suspicion that one would occur within the day. Sure enough, that night, one did. On the bottom there of Figure 13, harmonic tremor is plotted. Tremor pretty much followed the eruption itself; there was none before the eruption got under way.

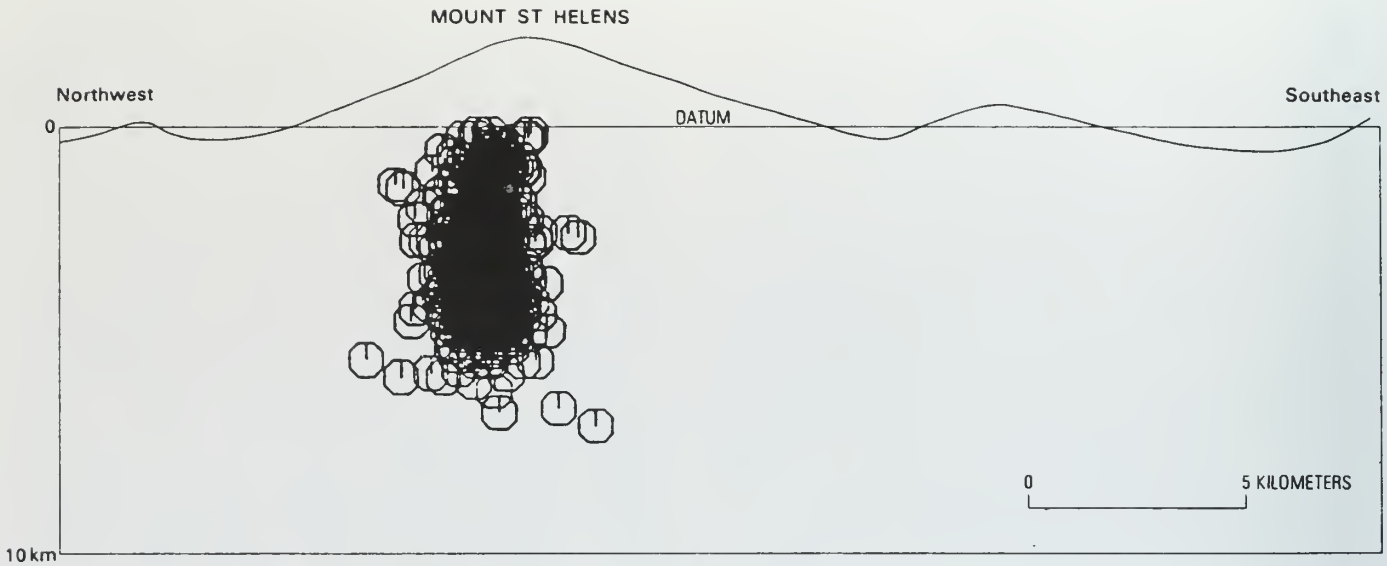


Figure 9. Cross section at Mount St. Helens showing distribution of shallow hypocenters under the north flank. Figure from Endo and others (1981).

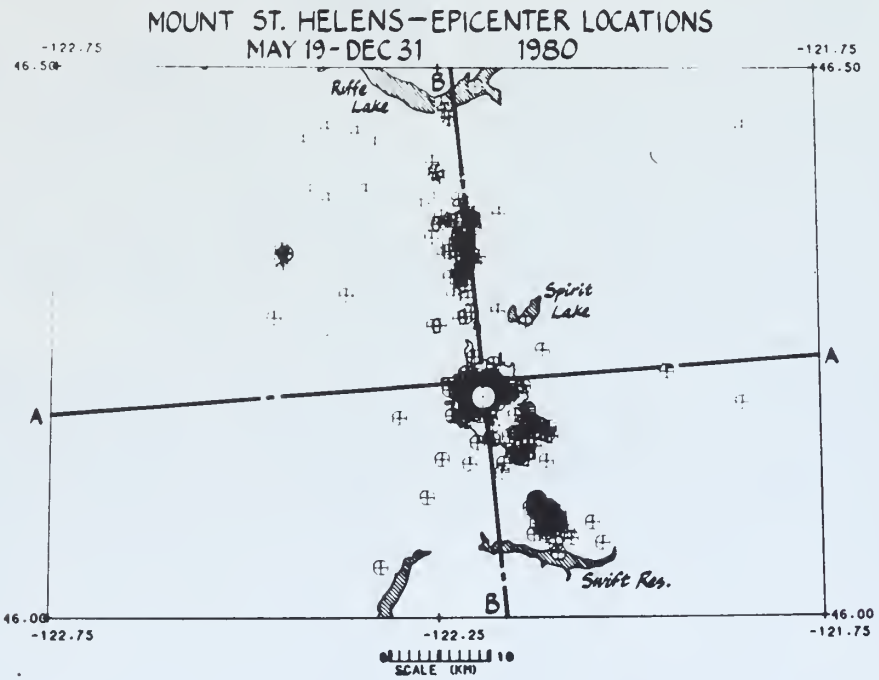


Figure 10. Distribution of epicenters north and south of Mount St. Helens for seven months after the May 18 eruption.

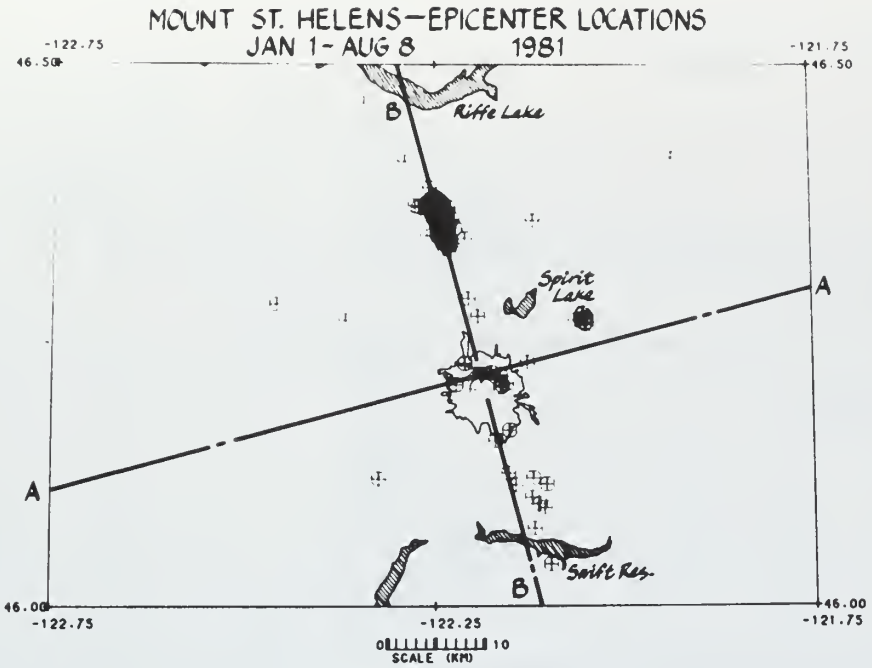


Figure 11. Epicenters from January 1 to August 8 of 1981 show a shift northward with a greater concentration 15 km north of the volcano.

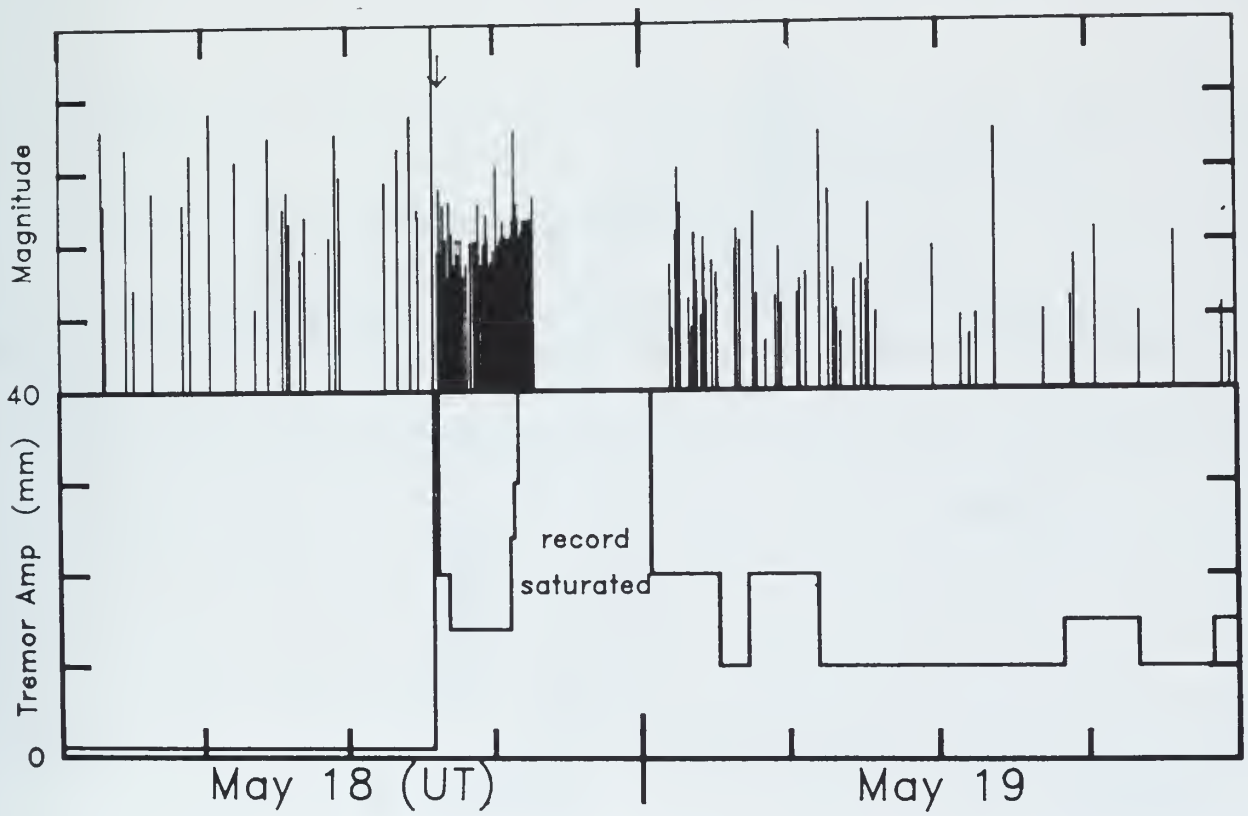


Figure 12. May 18 eruption seismicity. Each vertical line on the top portion represents an earthquake. Volcanic tremor is plotted in lower part of the figure.

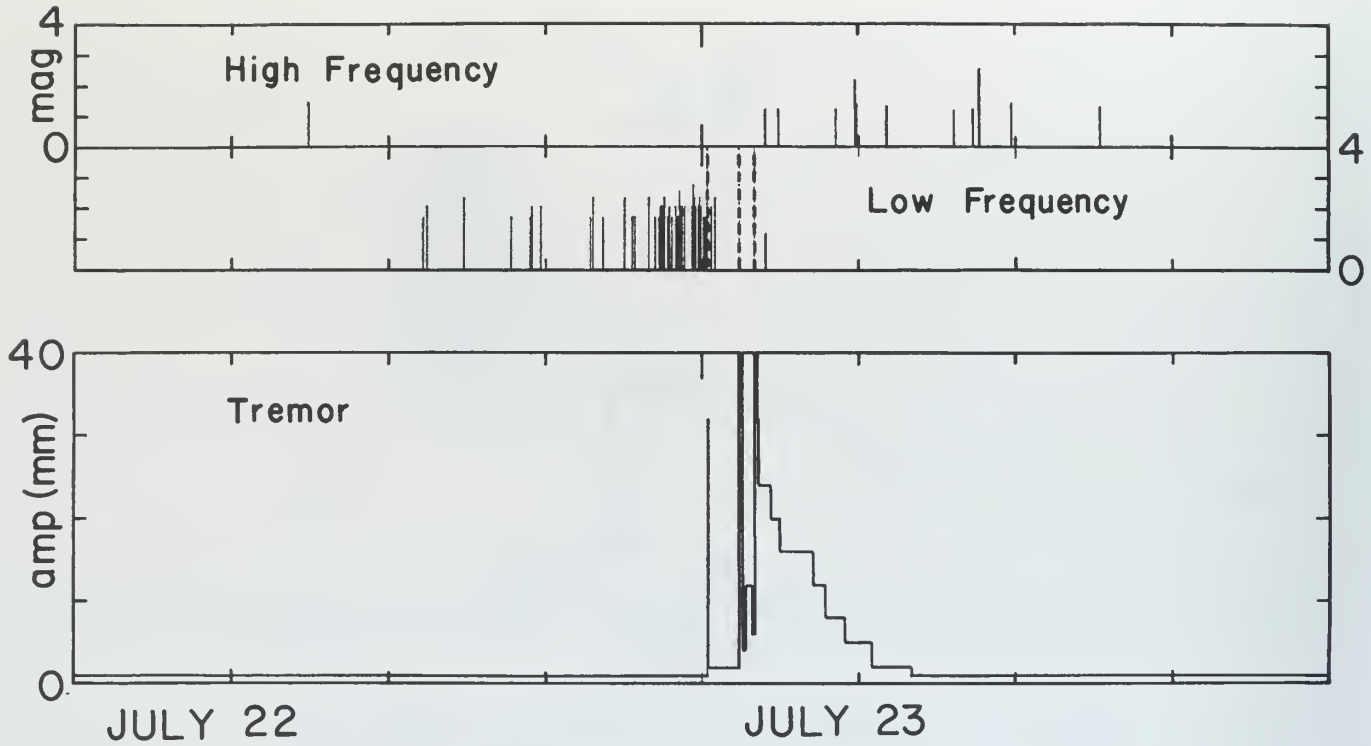


Figure 13. Low-frequency volcanic earthquakes served as precursor to the July 23 eruption. Period of eruption is approximately indicated by the harmonic tremor.

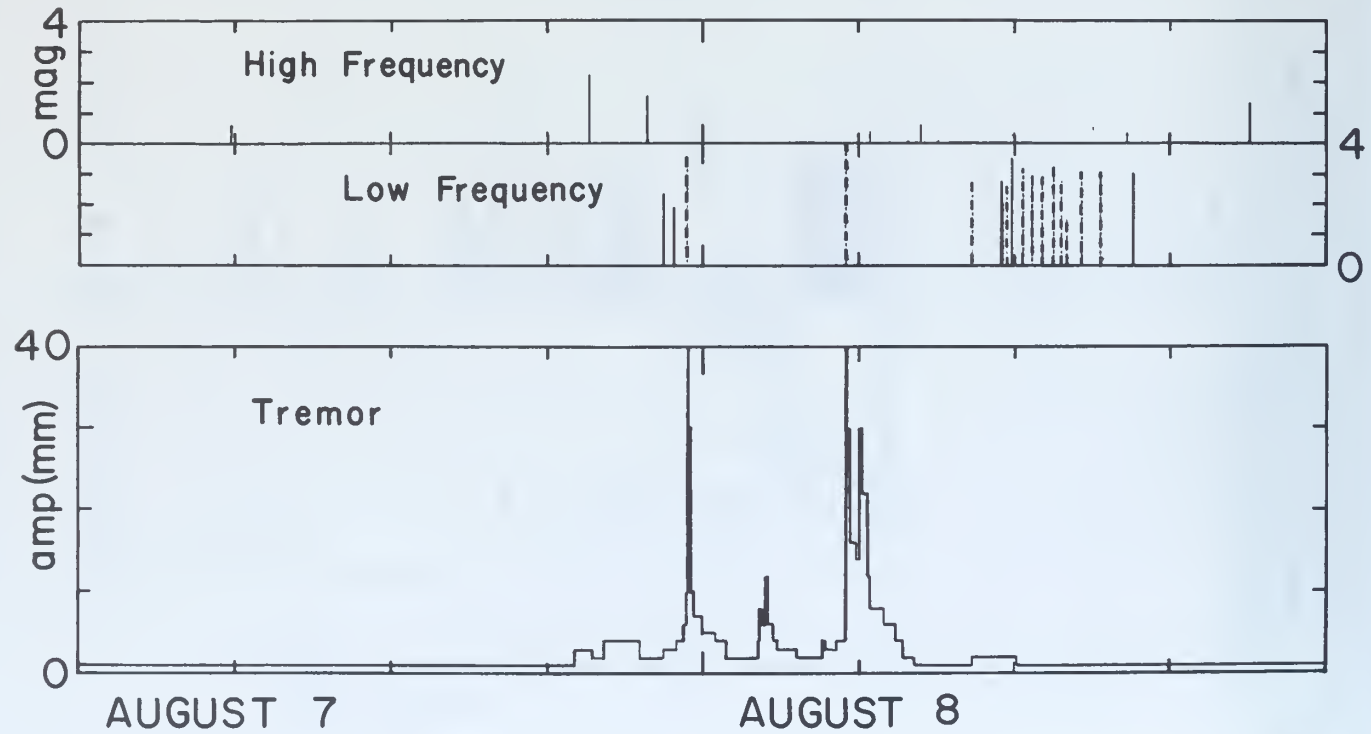


Figure 14. Harmonic tremor preceded the August 17 eruption. Volcanic earthquakes were not in evidence until after the eruption.

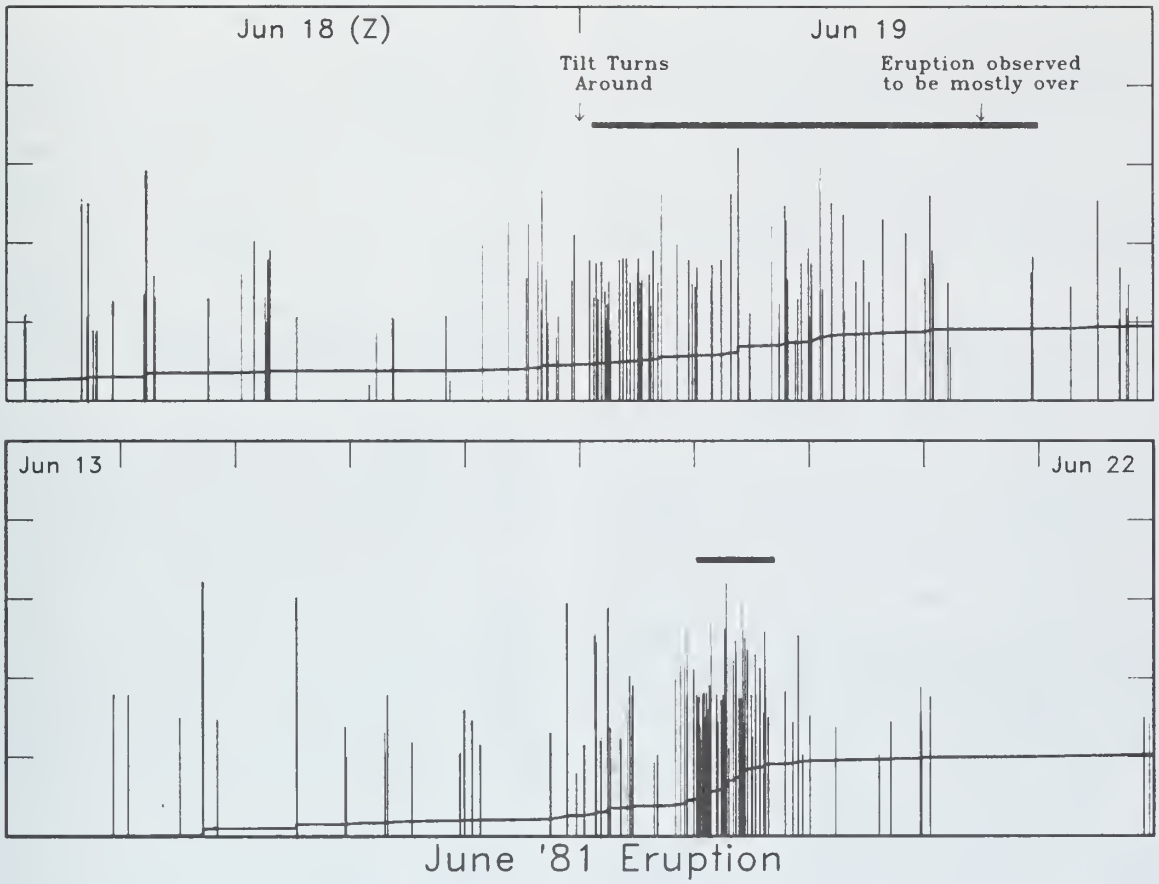


Figure 15. Seismicity associated with a dome-building eruption (of viscous lava). These have been generally successfully anticipated at Mount St. Helens.

A couple of weeks later on August 7, there was another eruption. In this case, small volcanic earthquakes did not precede the eruption, but several hours beforehand, harmonic tremor (Figure 14) was recognized which had not occurred since the eruption of two weeks before. An announcement was made that this type of change is what one might expect before an eruption. The loggers and the people in the area of the mountain got out, and the geologists went in. A similar pattern occurred in October. Shallow low-frequency earthquakes were again the precursor. An announcement was made several hours before this eruption that we thought something was coming. In this case, it came in four distinct batches or major plumes.

Since then, there have been no major explosive eruptions, but there have been a number of dome-building eruptions. Right after the October 1980 eruption, a small dome formed in the crater. That dome has remained intact in the sense that it hasn't been blown away, but it has been added to quite a number of times and is quite large now. Each one of these eruptions had some seismic activity associated with it, and was generally anticipated ahead of time. An example of the seismicity associated with one of these eruptions is shown in Figure 15, which shows the energy content within the events. We are now trying to distinquish a very important difference between precursor activity of explosive eruptions that would present quite a hazard and that of more ef- fusive events that aren't as hazardous. There seems to be a little difference in the seismic pattern, but we do not understand why.

APPLICATIONS IN CALIFORNIA

How do these experiences that we gathered at Mount St. Helens apply to California? Of course, the specifics of it probably do not apply at all. There is no reason at all to believe that the same type of phenomena would occur before an eruption here. Seismic monitoring will, however, remain the most important general preoccurrence monitoring technique. There are now a number of seismic networks all over the western United States. In fact, no activity like that at Mount St. Helens could go unnoticed anywhere in the western United States. The interpretation of the seismic data is a different matter. If unusual seismicity occurred right at a known volcano, then one is going to be much more suspicious of a volcanic type of an event. I would say the existing networks within the State of California are adequate to pick up the early warning signs of any major type of activity likely to occur. I thought it was quite interesting that Dr. McBirney said that he didn't think that the really big type of eruptions could go unnoticed anywhere now. I fully concur that in California seismology is probably going to be the tool that will see an impending eruption at the beginning. The question then is interpreting the events that are recorded. Are they related to a coming volcanic event or are they tectonically related?

In addition to operating networks, there must be the ability and willingness to respond rapidly once it is recognized that there is something seismically unusual going on. I gather this certainly exists in this state. The California Division of Mines and Geology have a portable network, and they have demonstrated at Stephens Pass and at Mammoth Lakes the ability to zoom immediately to the field to get additional seismic data. There are other institutions that have this capability also. One thing I would also like to strongly recommend is that there be a diverse group of organizations and institutions involved with this type of work. I think that is the case in California. The universities, the state itself, the U.S. Geological Survey, and even some private industries run networks. This promotes a sense of friendly competition and improves the quality of the data and interpretations that can result. What one group will miss, someone else will pick up. Don't put all your eggs in one basket. This is an obscure plea not to have something like the "Cascade Volcano Observatory" of the USGS, an organization that is "responsible for the whole works." Keep lots of different institutions involved and supported.

On the other hand, when it comes down to the crisis situation, it is not very wise to have a number of different voices yelling at the civil and public authorities at the same

time. At that point, the scientists somehow must get together to figure out what is going on and explain it in a unified way. I think that is really what happened at Mount St. Helens under the guidance of the USGS. There was not a problem similar to that which occurred on Guadaloupe a few years ago in which there were many different groups and conflicting scientific ideas that were aired publicly. That was quite confusing and unfair to the civil authorities. They need to know who and what to believe. They often just need a number, even if it is wrong, from someone or some group which they trust.

DISCUSSION

Question: In regard to determining the depth of the earthquakes, when you had only one station nearby (at 50 km), what was your estimate then of the depth of the event? How did it evolve into shallower and shallower determinations, and how long did it take to zero in on the depths?

Malone: If you start off with only a single station nearby, you don't have good depth resolution, this is true. For the first event, we didn't have very good depth control. We estimated it at being less than 5 km, but that was all we could say. That was simply because there weren't very many stations in the area. As more stations were added, our resolution apparently improved, but there was still a lot of scatter, because we didn't have a good velocity model. There are two types of problems that can be generated. The result there was that one of our early computer runs determining the depth produced some very wild sort of depths. Those depths were publicized very early before we had a chance to carefully look at the data. The pretty fancy computer equipment that we had there was in-house, and the on-line system was recording, but none of the analysis equipment was operating. In the early days of Mount St. Helens, we were doing everything by hand, and there were a lot of mistakes. I'd hate to have to go through that type of process again. As we improved the station coverage and the velocity model, the depths have converged on this very shallow type.

Question: What is your depth resolution now?

Malone: The resolution of what the depth is, of course, is proportional to the depth. As it gets very shallow, you lose resolution. We probably have it within a kilometer.

Question: You indicated that the earthquake triggered a premature eruption on May 18. Would you describe how you arrived at that conclusion?

Malone: We didn't see any precursor activity to the May 18 eruption that was similar to the precursors of other eruptions. That is one way of explaining our way out of not predicting it. I guess maybe that is the safest thing to do. It is an excuse.

Question: Could it not have been the reverse? That is, the earthquake was triggered by a volcanic mechanism?

Malone: I think both from the seismic and the photographic evidence -- and certainly the one that Rick Kienle showed -- it is very clear that the avalanche preceded the eruption by quite a bit. Many seconds went by before finally the eruption started. I think there is no question that the avalanche triggered the eruption. There is very good evidence also that the earthquake triggered the avalanche, just from timing considerations.

REFERENCES

Bennett, J.H., Sherburne, R.W., Cramer, C.H., Chesterman, C.W., and Chapman, R.H., 1979, Stephens Pass earthquakes: California Geology, v. 32, p. 27-34.

Endo, E.T., Malone, S.D., Noson, L.L., and Weaver, C.S., 1981, Location, Magnitudes and Statistics of the March 20-May 18 earthquake sequence, 1981, in Lipman, P.W. and Mullineaux, D., editors, The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 93-107.

McBirney, A.R., 1981, Realistic volcanic hazards assessment: The importance of frequency/explosivity relations, in this volume.

Sherburne, R.W., editor, 1980, Mammoth Lakes, California Earthquakes of May 1980: California Division of Mines and Geology Special Report 150, 142 p.

Unger, J.D., and Decker, R.W., 1970, The microearthquake activity of Mount Ranier, Washington: Seismological Society of America Bulletin, v. 60, p. 2023-2035.

Weaver, C.S., Grant, W.C., Malone, S.D., and Endo, E.T., 1981, Post-May 18 seismicity: Volcanic and tectonic implications, in Lipman, P.W., and Mullineaux, D., editors, The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 109-121.

THE CYCLICAL NATURE OF EXPLOSIVE VOLCANISM: A PETROLOGICAL APPROACH TO VOLCANO FORECASTING

Dr. William C. Melson
Division of Petrology and Volcanology
Smithsonian Institution, Washington, D. C.

ABSTRACT

There is typically a correlation between eruptive rock properties and eruption type in a given volcanic cycle. For many circum-Pacific, calc-alkaline volcanoes, a group to which most Cascade volcanoes belong, the highly explosive, catastrophic phases are related to breaching of water-rich dacitic magma. These produce great pumiceous tephra aprons and, nearer the volcano, pyroclastic flows. As the eruption progresses, deeper, less water-rich and often lower silica magmas are tapped with a corresponding decrease in explosivity and, hence, decreasing volcanic hazards. Thus, it is commonly the initial phase (but not always!) which produces the greatest destruction. It is also generally, but not always, true that the intensity of this initial phase is directly related to the period of repose between eruptive cycles. It is geophysical data rather than petrologic data that are critical in predictions of the time when a volcanic cycle will start.

Two volcanoes that are currently within eruptive cycles are showing systematic changes in rock properties and eruptive mode: Arenal Volcano, Costa Rica, and Mount St. Helens. Both these volcanoes had catastrophic opening phases involving the most acidic and water-rich magmas in their sequences. Modern rapid laboratory analytical methods have allowed monitoring of these changes in a timely way and are thus of some use in volcanic prediction. Volatile concentrations in melt inclusions in phenocrysts have been analyzed by ion probe. At both these volcanoes, volatile concentrations -- mainly water -- have been decreasing along with a trend toward more basic compositions. With these changes, the explosivity of the eruptions has decreased. Also, the gases in the vapor plumes have changed systematically in composition and in amounts at Mount St. Helens.

In 1975, about seven years after its catastrophic phase, Arenal Volcano returned for a day to highly explosive activity without a change in magma composition. One small canyon was devastated by hot avalanches and a sizable ash apron was produced. Although this activity was about on an order of magnitude less devastating than the opening phase, it points out the possibility of returns to explosive activity during the general trend of decreasing explosivity.

CYCLIC VOLCANISM

The question of concern to those of us who have been trying to predict explosive eruptions such as those typical of the Cascade volcanoes is: Do explosive eruptions follow repeating patterns? Is there a meaningful volcanic cycle model that we can bring to the field when we suspect a volcano is ready to erupt?

Some models for explosive volcanic cycles are being developed. More often than not, the greatest explosive activity is at the beginning of an eruptive cycle, a relationship which has impressed many volcanologists, such as G.A.M. Taylor (personal communication, 1970), who talked about the closed-vent phase of explosive volcanic eruptions

and the open-vent phase. This means that, after a volcano has been in repose for a long time, the conduit is sealed by solidification of magma from the previous eruption. Then a period of deformation occurs while the magma column rises up under the volcano. This closed-vent phase, which may involve phreatic explosions, but no release of new magma, has been observed in many, many volcanoes. It is followed by the catastrophic phase in which the vent is opened and quite different patterns of eruptions begin.

To illustrate how that scenario has occurred over the past 15 years, we can consider Mayon Volcano in the Philippines in 1968 (Moore and Melson, 1969). Mayon has short periods of repose but is hazardous because of its height, 2,462 meters above its base at sea level. Mayon has produced many hot avalanches during its relatively small eruptions, most of which were at the beginning of the eruptive cycle, as they were in 1968. Ulawun Volcano in Papua, New Guinea, in 1970 began its main explosive phase immediately after some initial symptoms (Melson and others, 1972). Arenal Volcano in Costa Rica, after only two days of mild seismic activity, had a catastrophic series of explosions (Melson and Saenz, 1973).

It is worth noting, too, that many volcanoes never get through the closed-vent phase. Some of those have been the controversial ones; for example, Soufriere of Guadalupe, which threatened to go into the open-vent phase, but didn't (Fiske 1981). Soufriere of Saint Vincent, in 1970, grew a small lava dome in its central crater lake, moving into the open-vent phase without major explosions, and then simply stopped. This is the kind of thing that challenges people who are attempting to assess the hazard. Do you evacuate towns and cities when you think a volcano is in the closed-vent phase and going toward the open-vent phase? Many times the vent doesn't open. And, then, sometimes it opens after being considered unlikely to do so, as in the case of Mount Pele's eruption at Martinique in 1902, where the city's population was devastated because political figures and others thought the volcano would not violently erupt.

Needless to say, each volcano has its individual history, but we can't ignore the collective experience we have on a worldwide basis. Although many volcanoes do have their unique personalities, they also have certain frequently repeated patterns. More often than not, when there is a well-developed closed-vent phase with all the deformations, a relatively complete cycle follows. During that cycle, more often than not, there are explosive eruptions, and rock types change; that is, we are dealing with zoned magma chambers. In addition, the magma column typically has a higher water concentration at its top.

To illustrate the idea of the volcanic cycle, and to present a model that, admittedly, may not work all the time, I'll describe two cases: Arenal, 1968 to present, and Mount St. Helens, 1980 to present. One we already know a lot about, and although some people would say it is fairly unique, Mount St. Helens in many ways isn't unique.

THE ERUPTIVE CYCLE OF ARENAL

Arenal Volcano in Costa Rica also isn't unique. It started erupting in 1968 and continues to the present day. It is one of those volcanoes that McBirney (1981) referred to as having a very long period of repose, over 100 years, and more typically 200 years -- so lengthy that before the catastrophic eruptions in 1968, it was not listed in the Catalog of Active Volcanoes of the World. It is a baby stratovolcano, rising only about 1,000 meters above its base.

On July 29, 1968, after no more than 48 hours of seismic activity, the volcano violently erupted. In this case, there was no warning other than the earthquakes experienced by the local villagers. There was no seismologist or geologist there to make predictions about what was going to happen. This is unfortunate because there were small villages devastated by the initial explosions. During the three-day period, the time in which the eruption moved into the open-vent phase, the area was destroyed and many lives were lost.

The closed-vent phase, the phase before the failure of the vent, was not more than

two days. This, in many ways, defies our ability to handle these situations. How can you get a population mobilized in a day or two?

The initial blast rose into the stratosphere to over 30 thousand feet. It was picked up as an air wave all the way to the United States. The main explosions were from the flank of the volcano. These opened a new crater and produced hot avalanches which moved first toward the little town of Pueblo Nuevo. Where the hot avalanches poured down the slopes, one could see features now familiar at Mount St. Helens. There were areas in which trees were blown down, bordered by singed or withered zones adjacent to fresh jungle (Figure 1). Some areas were totally devastated. The downed trees were blasted by ash-laden hurricane-like winds rather than a shock wave. Grass withered and ignited, suggesting temperatures on the order of 300°C as far away as 4 km from volcano.

Another thing that happened during this initial opening-of-the-vent phase, the catastrophic phase, was something we didn't see well at Mt. St. Helens: the ejection of large blocks to over 5 kilometers distance. Calculations show how much time those in the villages had between the explosions and impact. In less than a minute, the blocks were descending on the villages. The falling blocks devastated the area, leaving a terrain pockmarked with impact craters and ejecta (Figures 2 and 3).

POST-CATASTROPHIC ACTIVITY

Open-Vent Phase

Following the catastrophic phase was the purely open-vent phase, marked by the extrusion of a thick andesite flow following a period of renewed but much smaller explosions around September 13, 1968. The composition was changing very rapidly during this phase (Figure 4). Silica concentrations of about 57%, at the start, dropped very sharply. Changes in the mineralogy, mainly the disappearance or decomposition of hornblende, suggested that the water pressure also dropped. The highly porphyritic rocks of Arenal and Mount St. Helens contain nearly 50% crystals, of which plagioclase is predominent.

The explosion crater was later filled with lava which spilled out over the devastated zone. Over 90% of that devastated zone has now been buried by lava flows (Figure 5). When we see great lava flows, like those at the base of Shastina, we must remember that they may conceal impact craters and devastated terrain; sometimes volcanoes hide the evidence of their explosive phases.

It is typical after the opening of the vent and expulsion of pyroclastic material, that the expelled lavas are viscous and water poor. Part of the viscosity, I think, is due to isothermal crystallization. When the water goes off instantaneously, the crystallization point of the liquid is raised, causing very rapid crystallization in the magma which remains beneath the volcano. This causes the viscosity to increase very rapidly just after the explosive events. The fractionation trend during this eruption at Arenal shows that the initial explosive phase in these acidic lavas was about 57% silica. Within a few months, this dropped to 56% (Figure 4). From 1971 to the present, lava flows have remained at about the same composition.

The model seems to hold that many of these explosive eruptions are initiated by a magma column with a silicic top which is also water-rich. The magma column is not passive; it has the capability of forcibly moving upward into shallower reservoirs, and of destroying a volcano. The overpressure, as indicated by ejection velocities from the crater of Arenal, indicate up to 5 kilobars near the surface in one analysis (Fudali and Melson, 1972). So these magmas are capable of exerting tremendous overpressures.

Return of Explosivity

Another problem in the simple cycle of the open-vent phase characterized by quiet emission of lava flows or domes is the possibility of a return to explosive behavior. In the case of Arenal, the model seemed to work until around 1975 when, after building a large andesite lava field, an unexpected

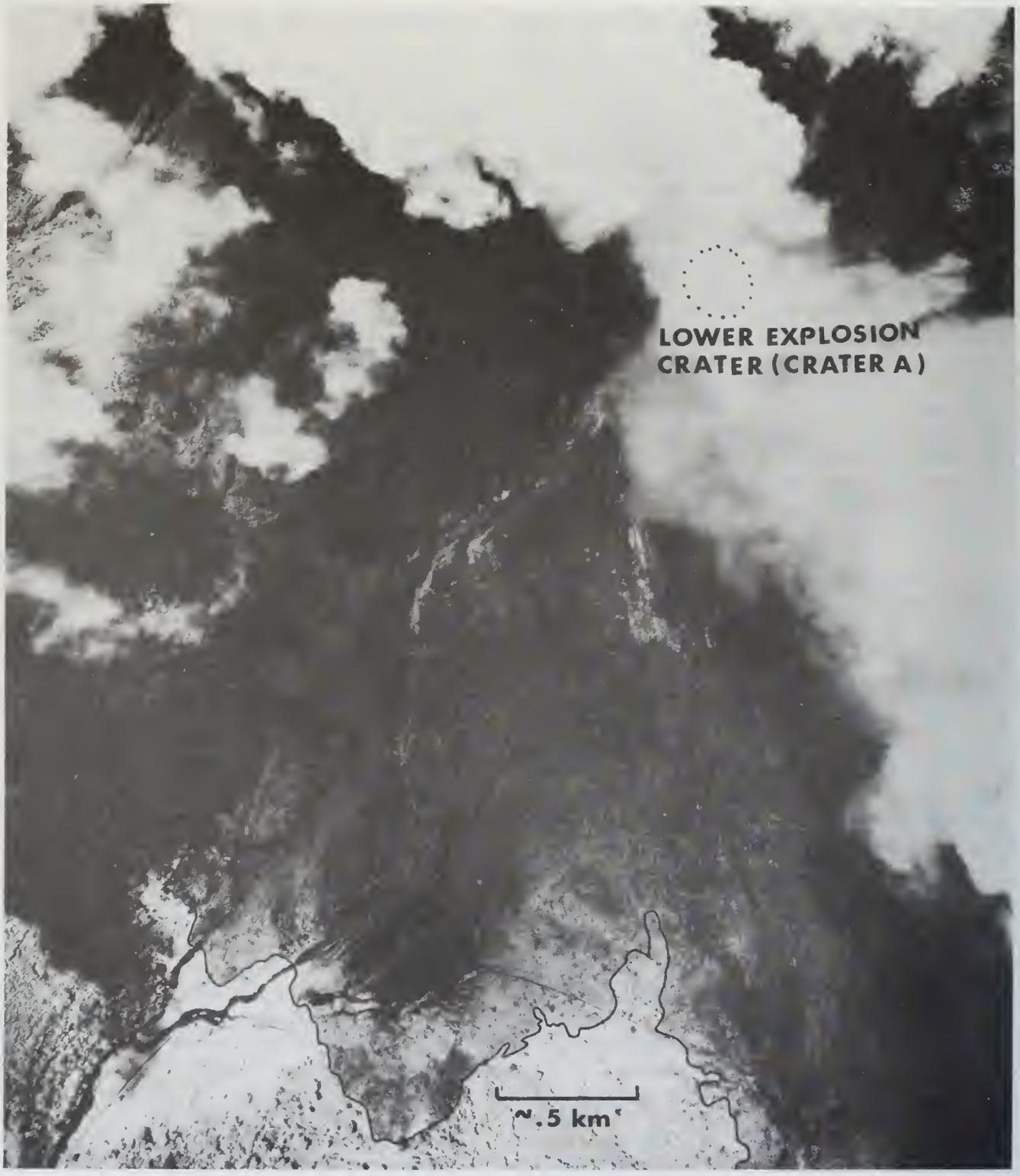


Figure 1. Areal photographs of the northwest devastated zone of Arenal Volcano, Costa Rica, after the catastrophic explosions of July 29-30, 1968. Sharp margin of the seared and devastated zone with unaffected pasture and rain forest is delineated. Courtesy of Costa Rican Instituto Geografico.

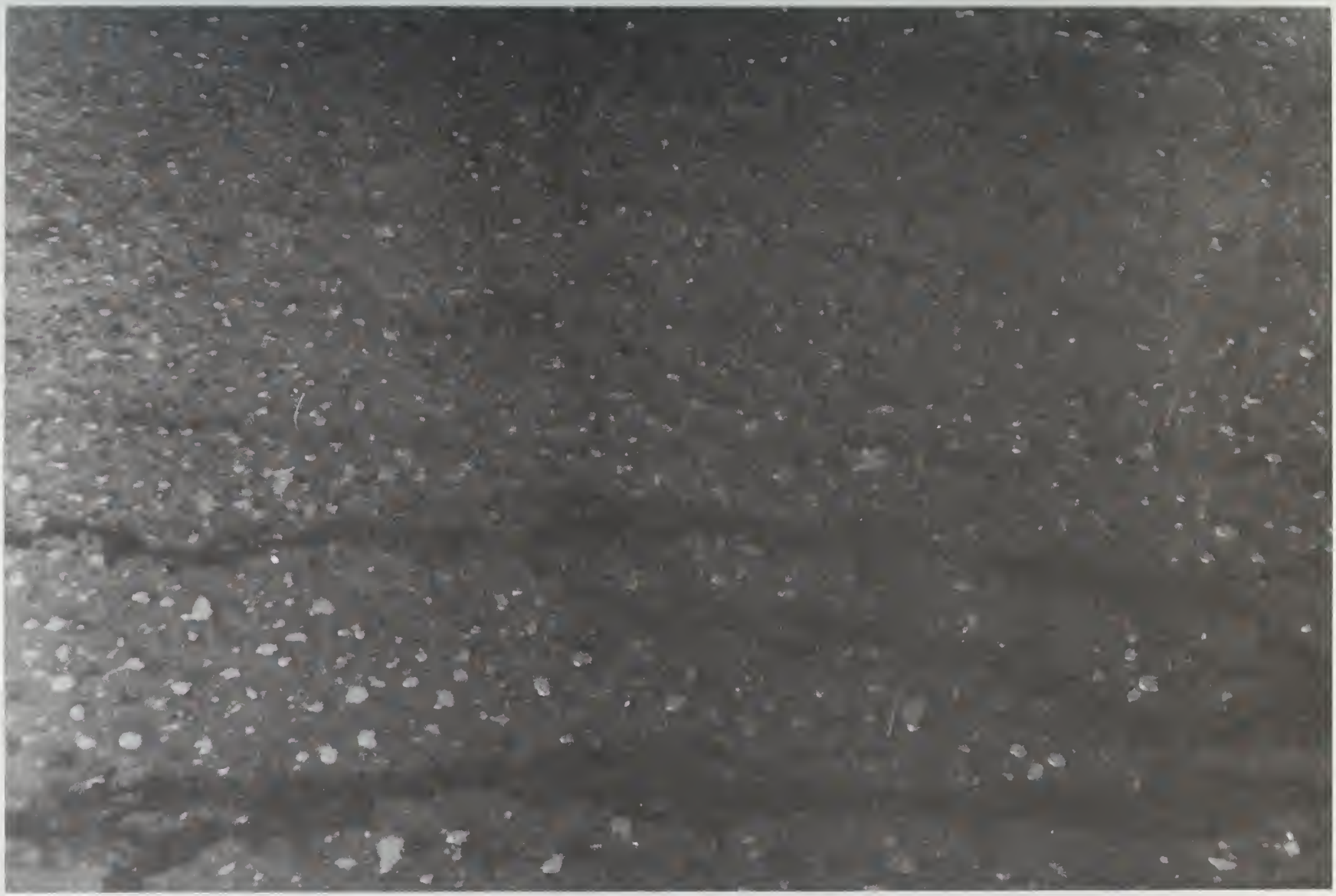


Figure 2. Part of the impact crater field after the explosions of July 28, 1968. Oblique low-level areal photograph. Note approximately 30 meter high trees in lower right-hand quarter of photograph. Impact craters were largely filled by water at this time from torrential rains during and after the eruptions. Arenal Volcano, Costa Rica.

Figure 3. Impact crater near the devastated village of Tabacon, near Arenal Volcano. Block ejected during the initial, vent-opening explosion of July 29, 1968.

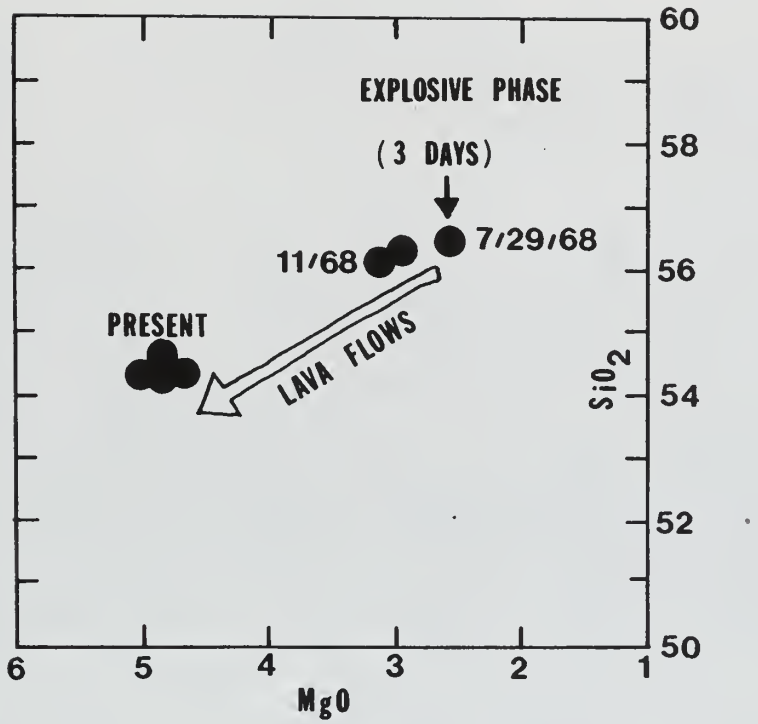


Figure 4. Relationship between MgO, SiO2 and time of eruptions for the 1968 and ongoing eruptives of Arenal Volcano. Analyses of early phases are from Melson and Saenz (1973). Work on the later eruptives (Malawassi, 1979) show that compositions have remained quite similar in recent years to those of this figure.

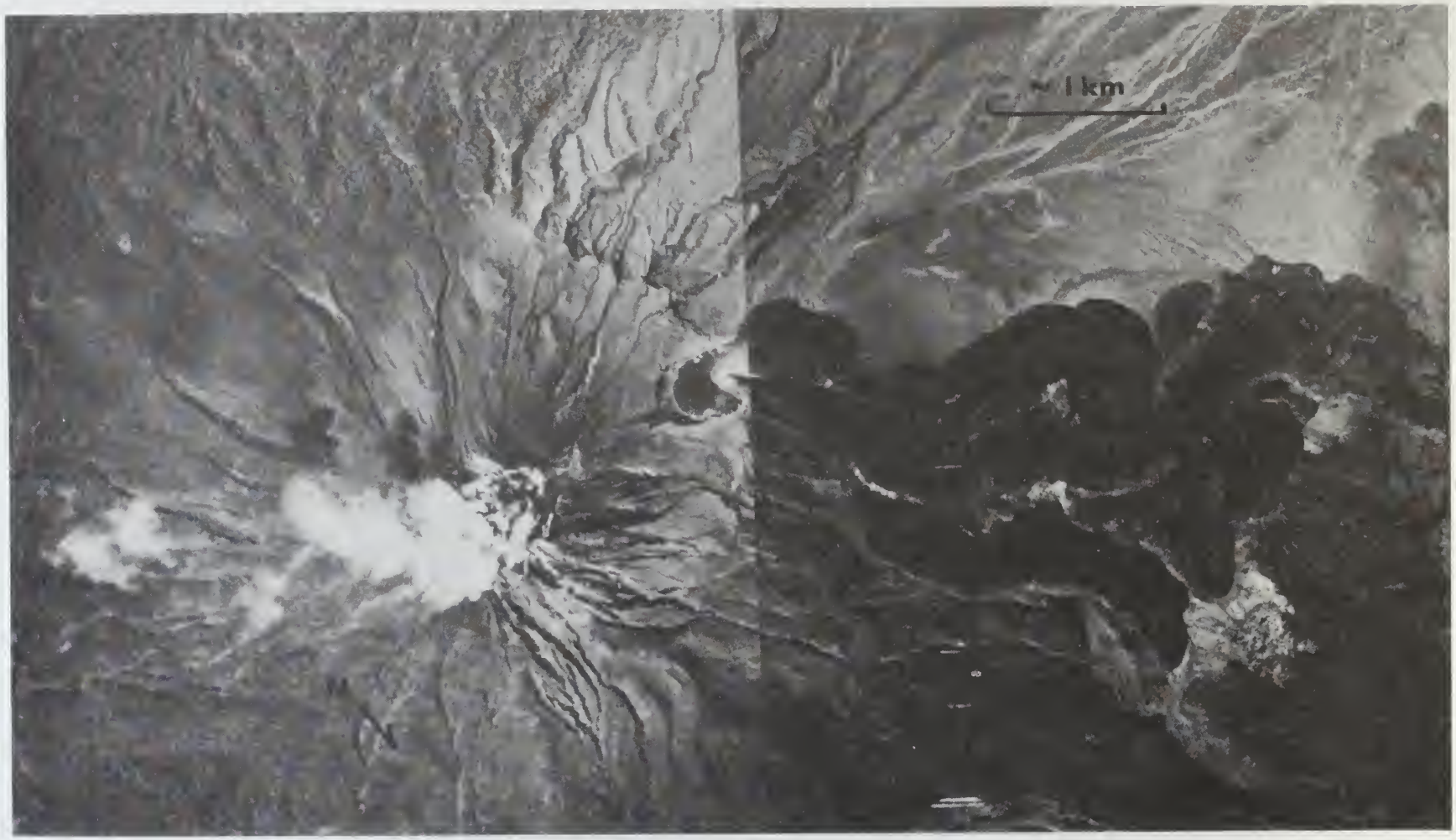


Figure 5. Basaltic andesite lava flows partially covering the devastated zone and emitted between September 14, 1968 and September 9, 1971 from Arenal Volcano, Costa Rica. Photos courtesy Costa Rican Instituto Geografico.

explosion occurred at the summit crater sending a nuee ardente a distance of 6 or 7 kilometers. This event was much smaller, by an order of magnitude at least, than the earlier big event. Fortunately, the area had been evacuated for many years so it caused no destruction, but it is instructive of the kind of thing that can happen during what seems to be a decline in the explosive activity of a volcano. This is the kind of thing that could happen at Mount St. Helens, just a slight return to explosive activity, when perhaps a pocket of water-rich magma rises up or the hydrostatic overpressure of the magma column otherwise gets very high. For whatever reason, there may be a large, rather rapid expulsion of magma, and then a return back to the quiet phase. The eruption at Arenal was over in half a day, and since that time, Arenal has had no renewed large explosions.

Deformation

We have been able to put tilt stations on Arenal Volcano. Although they are not operating at this moment, they were operating previous to a year ago, and we have two years of tilt data. The activity at the volcano during that period of time was one of continuous lava emission. We put in four stations at increasing distance from the rim of the volcano and saw a continuous deflation of the volcano (Figure 6A-B), indicating a very shallow magma chamber which is slowly emitting its contents. It is interesting to compare this to Kilauea where deflation of a similar magnitude can take place in hours. The tilt is measured in microradians (Figure 6B), one of which is equivalent to a millimeter drop in a kilometer horizontal distance. At Arenal we had a 100 micron drop over two years, a movement which could happen in a few days or less in Hawaii. This difference probably has to do with the difference in magma viscosity. Apparently, the magma of Arenal is so viscous that the tilt response is not as rapid, nor is the rate of emission as rapid.

EXPLOSIVE TEPHRA ERUPTIONS

There has been talk of the importance of working out the long-term histories of volcanoes in order to construct probabalistic models; that is, to study what happened during and between the periods of past eruption, so that when we encounter a new period, we might have some idea about what will happen next. We know that Arenal has had 11 major explosive events, for there are 11 major tephra zones, ranging in composition from dacite to andesitic basalt. In some cases, we see evidence of the zoning of the magma chamber in a single explosive episode, where gradations from white dacite to darker-colored andesite occur in a single unit. The gray dacite lapilli layers at Arenal are similar in composition to the major pumice eruptives of Mount St. Helens. Beneath each of the airfall lapilli layers, there is a well-developed soil zone. We have radiocarbon dates from three data points which indicate that Arenal built itself in less than 4,000 years by frequent large eruptions. By "frequent," I mean at 200- to 500-year intervals. After airfall tephra were laid down away from and down wind from the cone and more mafic lavas were added to the cone itself, there, on the cone and buried (Figure 5), is the missing part of the record that Dr. McBirney was talking about -- the part that is gone and will never be seen without drilling. When we look at the cone itself, we see mainly lava flows, but farther out in the surrounding country, if we're lucky, we find the evidence of the great explosive pyroclastic eruptions.

MOUNT ST. HELENS

You've heard a lot already about the closed-vent phase, and at Mount St. Helens, that phase had a peculiar expression: seismic activity, phreatic explosions, the development of the bulge, and the loss of the initial summit craters as they merged into the great graben-like structure as the north slope broke loose. The bulge was not so obvious during this initial phase as was the tremendous development of the notch. During the closed-vent phase, we, like most people, had the suspicion it wasn't going to last.

Starting with the May 18 eruption, which initiated the open-vent phase, the early Mount St. Helens eruptions were mostly of pumiceous tephra and ash. The pumices

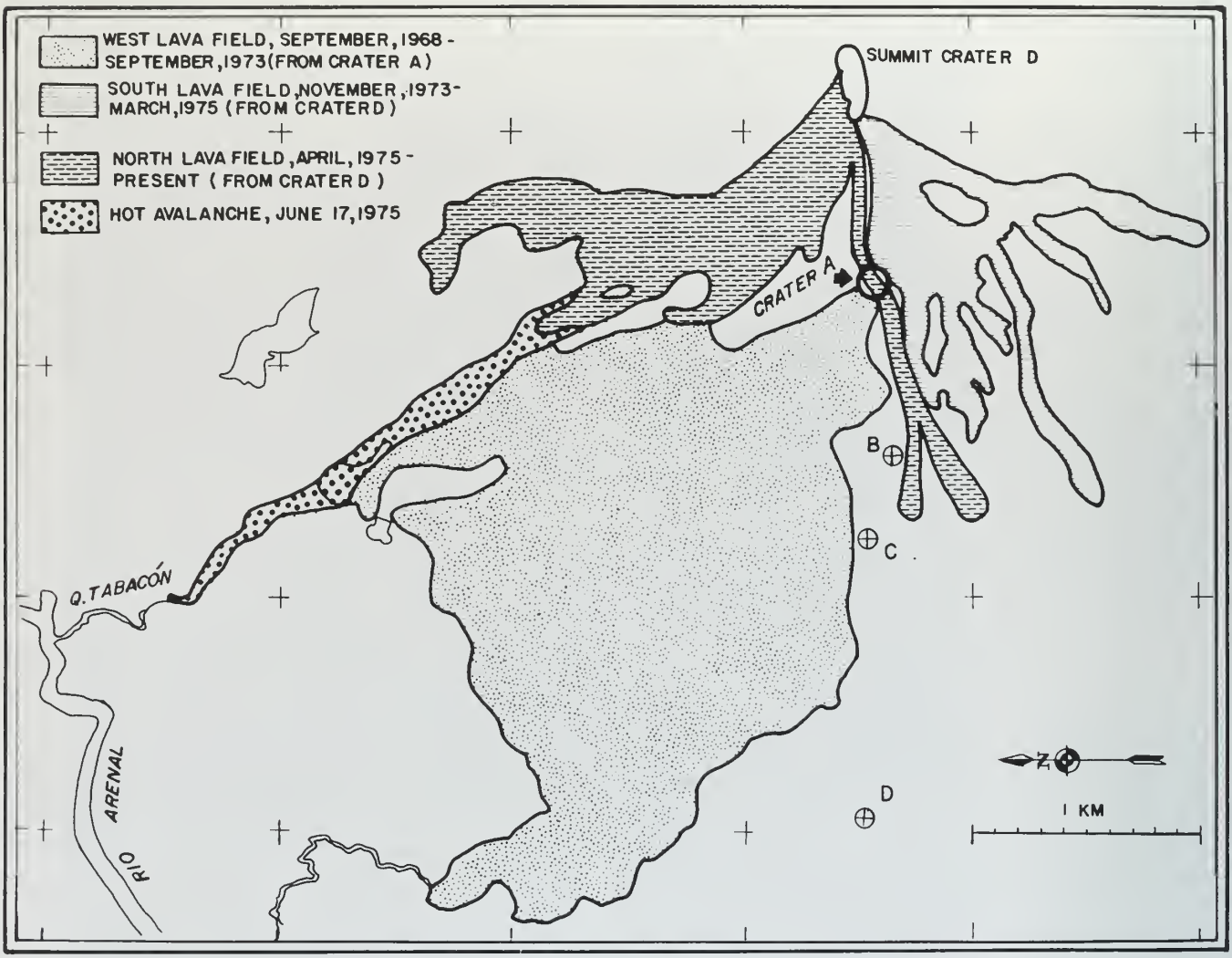

WEST LAVA FIELD, SEPTEMBER, 1968 - SEPTEMBER, 1973 (FROM CRATER A)
SOUTH LAVA FIELD, NOVEMBER, 1973 - MARCH, 1975 (FROM CRATER D)
NORTH LAVA FIELD, APRIL, 1975 - PRESENT (FROM CRATER D)
HOT AVALANCHE, JUNE 17, 1975
SUMMIT CRATER D
CRATER A
B
C
D
Q. TABACÓN
RIO ARENAL
1 KM

Figure 6A. Locations of dry tilt stations at Arenal Volcano, and rate of change in tilt (deflation) along a vector pointing toward the summit crater (see Figure 6B). Measurements start October 19, 1976. Station A, not shown on the figure and the one closest to the volcano, was isolated and eventually covered by lava flows from the summit crater shortly after the station was installed. Tilt measurements done in co-operative program with the Instituto Costarricense de Electricidad.

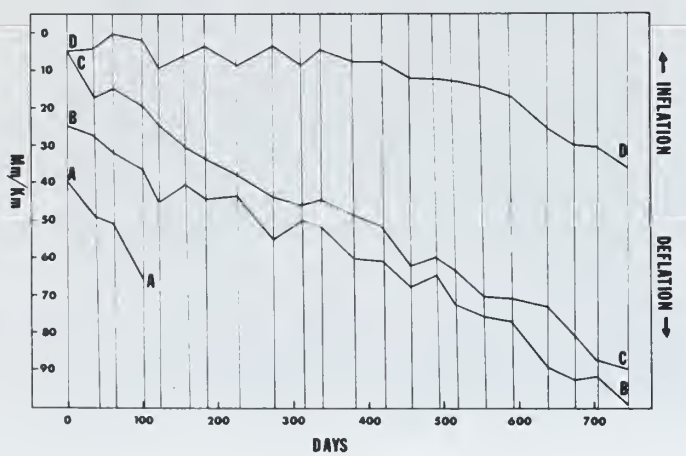


Figure 6B. Rate of change in tilt (deflation) along a vector pointing toward the summit crater.

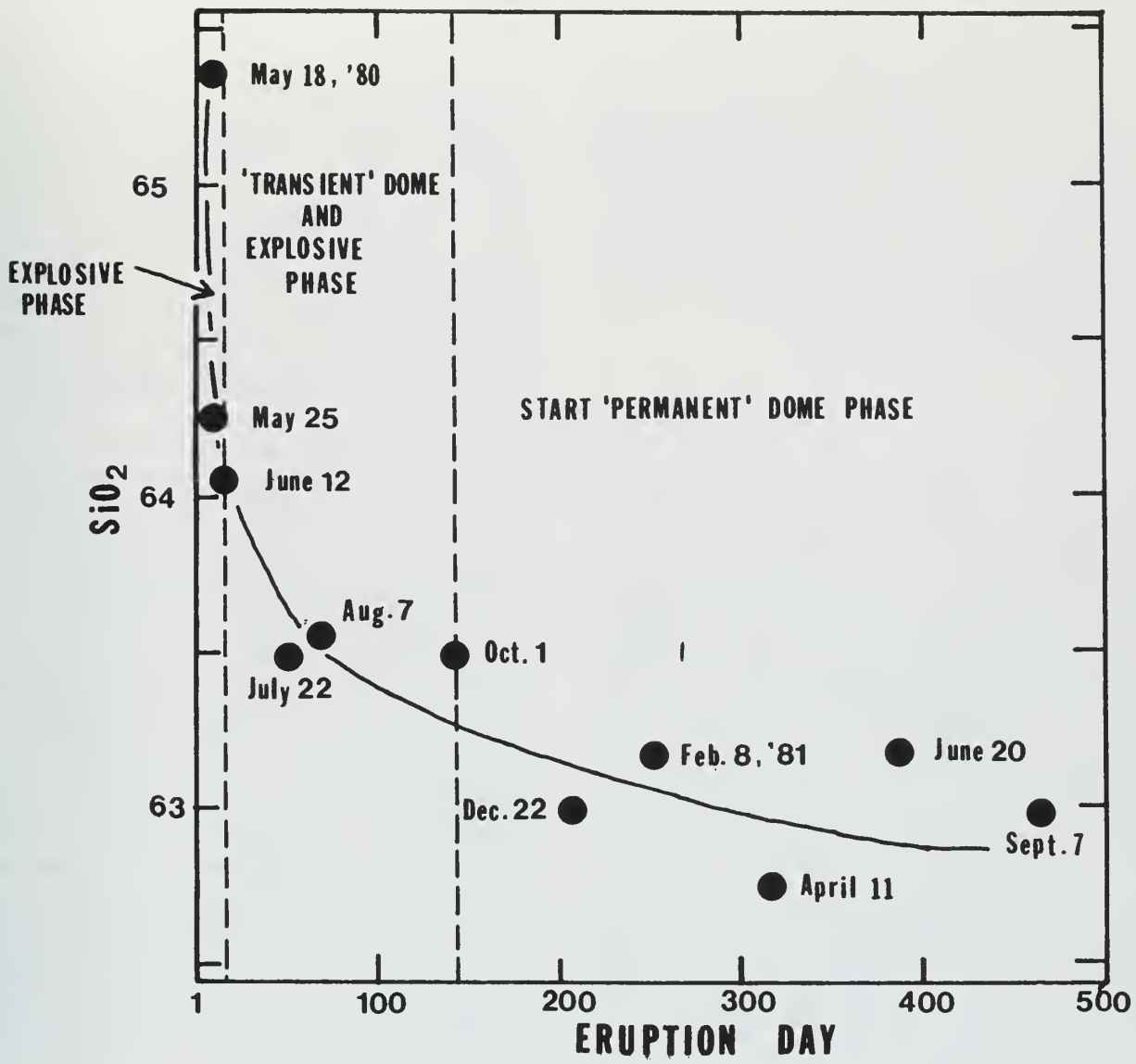


Figure 7. Relationship between average SiO_2 contents for the eruptive rocks of each episode of activity, eruption time, and type of eruptive activity during the 1980-81 eruptive sequence of Mount St. Helens. The SiO_2 content is the average of a number of samples from each eruptive episode. The values and trend are similar to those reported by Lipman et al. (1981). The chemical analyses reported here were done at the Smithsonian by classical wet methods and by electron microprobe analyses of fused powders.

themselves are highly porphyritic, containing hornblende phenocrysts which were undecomposed; that is, stable, under the very high water pressures under which the May 18 magma emerged.

Following the catastrophic opening of the vent, there began a period of what you might call transitory domes where lava that did make it to the surface or that plugged the vent was repeatedly blown out. This period lasted from June 12 to October 16, 1980 (Figure 7). Pumice flows were erupted repeatedly during the time of these transient domes. These showed considerable petrologic diversity. In October of 1980, the "permanent" dome was formed, and it continues to periodically grow.

VARIATIONS OF VOLATILE CONTENT

Some of the plagioclase phenocrysts have provided one of the very valuable features of these rocks. Many andesites and dacites contain phenocrysts having glass inclusions which commonly appear in thin section as shadowy zones within the crystal. Anderson (1975) and others have expressed much interest in such inclusions because they may represent the composition of the pre-eruption magma. As the crystal was growing in a liquid beneath the volcano, it grew very rapidly at times and trapped the liquid in which it was growing. If this has happened, the volatile concentration in the crystal should be meaningful; whereas, the matrix glasses comprising the remainder of the rock were exposed to atmospheric pressures and this exsolved most of their pre-eruption volatiles. This claim is supported by microprobe analyses which show that the matrix glasses have sums about 99%; whereas, the melt inclusions for the same eruption have sums of 92% to 93% typically (Figure 8). The deficit of 7% in the May 18, 1980 pumice (Figure 8) is interpreted to represent the volatile content which cannot be analyzed by the probe. The only likely candidate is water because we can't analyze for hydrogen, although we have analyzed for fluorine, chlorine, and sulfur. These compose less than 0.2 weight percent. With modern instrumentation, which was not available 15 years ago, we can now analyze these inclusions with the electron microprobe -- or even more powerfully, in terms of actually getting direct hydrogen determinations, we can use the ion microprobe. Preliminary ion probe analyses done by Stan Hart at M.I.T. indicate equivalent water concentrations of up to 7 percent in May 18, 1980 melt inclusions.

In some cases, in the pumices of the May 18 eruption, and even in those of the ancestral cone, some melt-inclusion-rich crystals actually exploded upon eruption. If the melt inclusion were large, the crystals could not stand the overpressures within them. This is seen by cavities in the pumices, lined by pieces of plagioclase or hornblende, which I interpret as exploded crystals. Only the very small inclusions would generate such small total pressures that the crystal walls could withstand them.

The melt inclusions had inferred water concentrations of about 7% on the eruption day, May 18, in the pumice eruptions (Figure 8). Evaluations made of the pumice and of the gray dacite, which is also know as the "blast facies," indicate slightly lower water concentrations (Figure 8), but still very significant. Overpressures on the order of at least 5 kilobars are necessary in order to have this amount of water dissolved in liquids with the rhyolitic compositions of the melt inclusions. This is the equivalent of about 15 kilometers of lithostatic pressure. A magma like this confined immediately beneath the volcano can exert a pressure of that magnitude. It makes you wonder if an eruption associated earthquake could be the result of the overpressures rather than the cause of the volcanic eruption. The tectonic setting allows magmas to move, but the magmas have their own properties, and in a search for causality, the relationship of the magma pressure effects cannot be left out.

Studies of melt inclusions from successive explosive eruptions show the volatile content dropping from 7% on May 18 to a level of 4% maximum concentration on August 7. This was during a time of periodic pyroclastic eruptions. Similar high water pressures (Figure 8) are recorded in fluid inclusions from prehistoric explosive eruptions -- namely, the T and W pumices

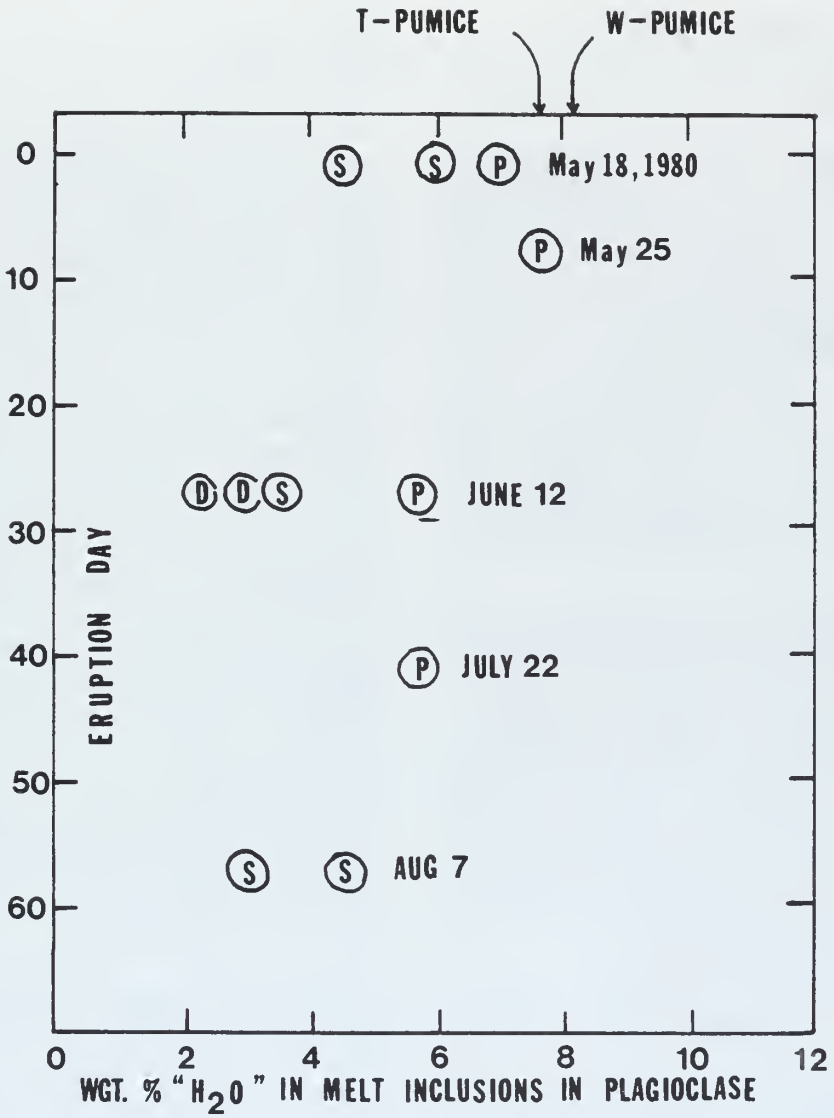


Figure 8. Relationships between inferred water content in melt inclusions in plagioclase, time of eruption, and rock type in the 1980 eruptive sequence of Mount St. Helens. Rock type key: P = pumice, density <1. S = pumiceous (density> 1). D = dome rocks. Water content inferred as the difference between 100 percent and the actual sum as determined by high accuracy electron microprobe analyses.

(Crandel and others, 1962). By contrast, water concentrations in the domeforming lavas are much less. The domes through September of this year are typically around 2% water.

VARIATIONS IN SILICA CONTENT

Bulk versus Glass Composition Variations

Not only do water concentrations change, but silica drops also. The initial explosions contained about 64.5% silica, although these figures have been refined recently because we have now found what looks like essential pumice in the avalanche itself. It is the most fractionated material we have, at about 66% silica. Successive analyses indicate that with the initial May 18 eruption, the silica concentration dropped in a short time to 62%. Thus, we see a compositional change from dacite to andesite in the Mount St. Helens magma (Figure 7).

It is fortunate that the Mount St. Helens' dacites have ilmenite and titan-magnetite in them, because we can determine pre-eruption temperatures from them. They show a magma temperature on May 18 within a range of 990° to 1,010°C. Successive data do not indicate much of a trend. This is interesting because it shows a great amount of crystallization taking place and supports what I think is an isothermal model of crystallization due to water loss.

Viscosity

In considering the variation with time of silica concentration at Mount St. Helens (Figure 7), we see the white pumice of the debris avalanche at 65% in a number of analyses. By May 25 and then June 12 in the airfall tephra, it dropped to nearly 64%. By August 7, it was down to 63.5%, and then, in the dome pumices all the way through September (Figure 7) and even through December 22, the data are scattered at around the 63% level. The reason that this is interesting is that bulk silica concentrations much lower than this are in the range which magma more typically takes the form of lava flows (Figure 9). But during the period of decrease in silica, the viscosity did not drop, as one would normally expect. The reason the Mount St. Helens eruptions aren't very fluid, even though the silica concentration has been dropping, has to do with the rapid crystallization behavior. On May 18, 1980, the pumiceous magma that came out was about 65% glass (Figure 10), and the silica concentration of the matrix glass was about 70%, which is relatively low -- in fact, the lowest in the sequence. Then the rocks became more crystalline so that now we have only about 30% to 40% glass left, with a rise in the K_2O content of the matrix glass (Figure 9). By the time the glass K_2O has reached 3%, the bulk rock composition has not changed much, but the glass has changed a lot. Again, the reason is that the rock is crystallizing, and even though the overall silica concentration has dropped, the viscosity remains extremely high because the amount of liquid is small and has been enriched in silica, alumina, and potash. By the time the bulk glass content was about 40%, it contained about 78% silica and 12% alumina, and was incredibly viscous. This is an interesting point because we often think we can determine the viscosity by looking at the bulk composition, which is true for homogeneous liquids. However, this is a rare situation in volcanoes of this type, which are characterized by highly phyric lavas, so you really have to consider the composition of the matrix glass and remember that the increase of crystals in the rock increases the viscosity of the bulk rock even further.

Figure 9 shows compositional plots of current and prehistoric eruptive types from Mount St. Helens. Explosive-phase pumices from pyroclastic flows and tephra eruptions fall in the 66% to 68% SiO_2 range. This includes the May 18 pumice and that of the sixteenth-century "W" pumice. The domes tend to fall as low as 62%. The flows begin at about 62% silica and overlap with the domes, and they continue on to even lower SiO_2 concentrations. The current trend of erupted material is shown by the black dots. One might speculate that we are near to having flows, but we have to have some kind of increase in the eruption rate or something that stops the magmas from crystallizing so rapidly before we'll see any major change. Many have commented that some of the caps on the domes are actually

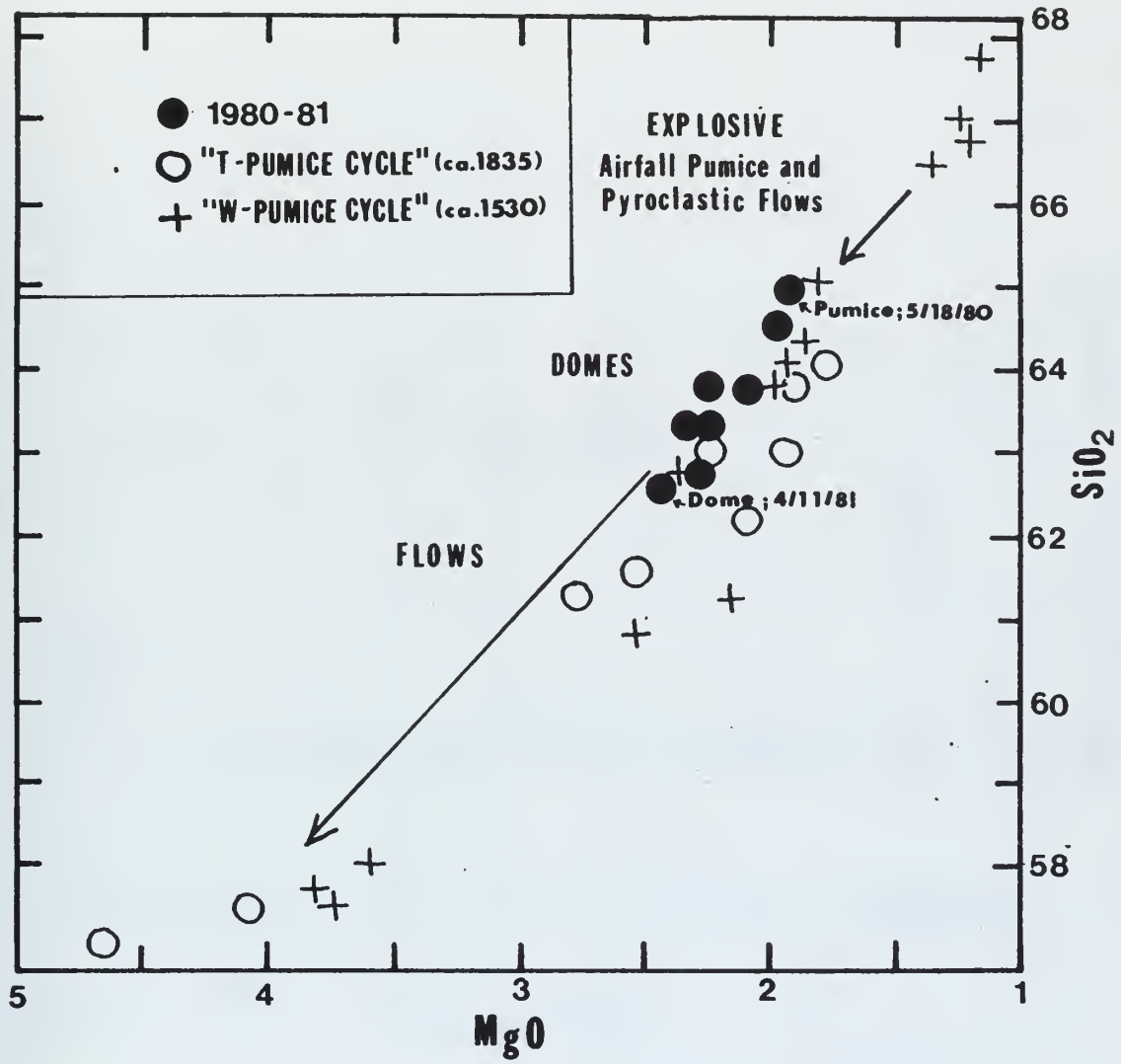


Figure 9. Relationships between MgO and SiO_2 contents and eruptive modes in the three most recent eruptive episodes of Mount St. Helens. Analysis of "T-Pumice Cycle" and "W-Pumice Cycle" is based on samples provided by Prof. C. A. Hopson which were analyzed at the Smithsonian by classical wet methods or by electron microprobe analyses of fused powders.

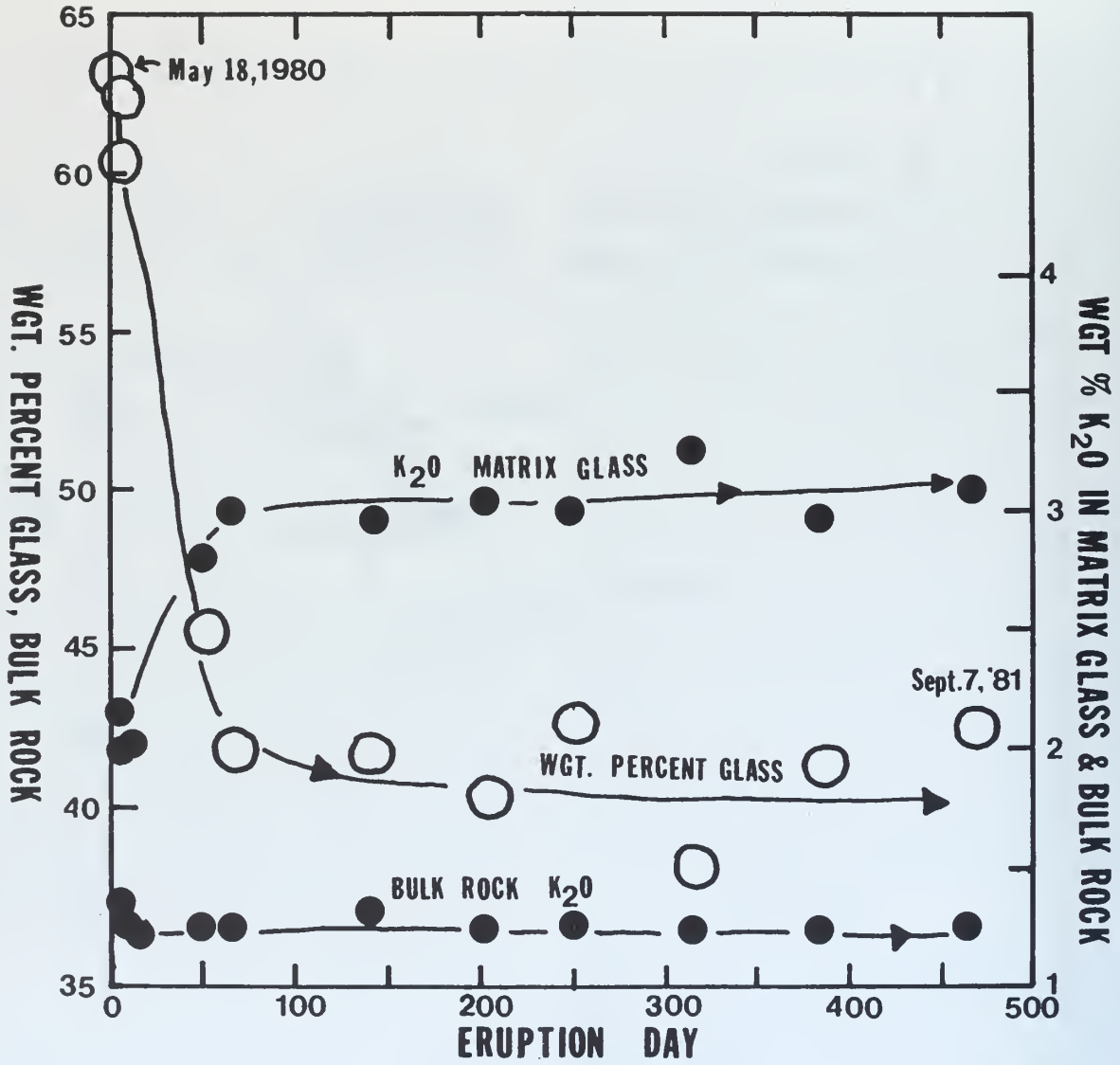


Figure 10. Relationships between amount of glass in bulk samples, K_2O content of matrix glass and of bulk rock and time of eruption in the 1980-81 eruptive sequence of Mount St. Helens. Amount of glass in bulk sample was calculated from bulk and matrix glass K_2O content assuming K_2O behaved as a perfectly incompatible oxide during the progressive crystallization of the rocks, and was concentrated in the residual liquid, now the residual matrix glass. This is approximately true as no K_2O-rich phases, such as K-spar, occur in these samples, although there is a small amount of K_2O in the small amount of hornblende present.

flows, and that if the volumes had been larger, we'd be seeing typical lava flows.

ACKNOWLEDGMENTS

Special acknowledgement is in order to Roger Martin and the others who have assisted in the editing of the transcripts on which this paper is based. The results reported here would not be possible without the assistance of Don Swanson, Cristina Heliker, Kathy Cashman, Dan Dzurisin, Mike Dukas, and others of the U.S. Geological Survey Vancouver office who provided many samples from the ongoing eruption of Mount St. Helens. At the Smithsonian, Tim O'Hearn, Richard Johnson, Frank Walkup, Joe Helen, Gene Jarosewich, and Vic Krantz contributed substantially to the Arenal and Mount St. Helens sample studies. Stan Hart, M.I.T., and John Delaney were and are responsible for ongoing ion microprobe analyses of melt inclusions. In Costa Rica, Jorge Umana, Rodrigo Saenz, Eduardo Malawassi, and Jorge Becquero have contributed to the Arenal results here reported. Much of the field work reported here was funded by a number of grants from the Smithsonian Fluid Research Fund through S. Dillion Ripley and from the Sprague Fund, handled within the Department of Mineral Sciences by Dan Appleman. The Mount St. Helens results here reported are part of an ongoing collaborative study with Cliff Hopson, University of California at Santa Barbara. Clive Kienle, Foundation Sciences, has assisted in many ways during the Mount St. Helens work. All this support is gratefully acknowledged.

DISCUSSION

Question: What takes the place of silicon dioxide as it diminishes in the lavas?

Melson: It is an increase in iron, magnesium, and calcium, largely. The magma becomes more basic as the SiO_2 decreases.

Question: Why is the gray dacite, though it has a similar water content, so nonvesicular compared to the pumice?

Melson: The gray dacite is interpreted to represent the cooling magma head at shallow depth which was degassing and cooling. When it came out, it was already 70% crystallized, based on the matrix composition of its glass. So, (1) it had leaked gas as it crystallized, and (2) there was very little gas left. As a matter of fact, some of the gray dacite is transitional with pumicious dacite. Some of the airfall ejected gray dacite is scoriacious, and there is also a very dense variety.

Question: Where did the gas go?

Melson: Presumedly leaking out of the system. Small quantities getting into the phreatic explosions -- coming up through the cracks. I mean, we do know a lot of gas came out of there during that time.

Question: I was under the impression that there were no magmatic gasses released prior to May 18.

Melson: I don't know that you could detect the amount that could be leaking into the hydrothermal system when it is just being swamped with melting glacial ice and such.

Question: Some researchers have come out with a much smaller figure reported last spring -- like 1% water or less.

Melson: That's impossible. The reason it's impossible is because you can't grow hornblende very well in that kind of liquid. You see, this isn't just the melt inclusion data, but phase equilibria information also supports very high water pressures. And we've done ion probe work on it. Unfortunately, we do not have reproducible results yet, but we will. We have two runs: one shows very high water concentration in the ion probe, the other shows very low. The microprobe repeatedly shows low sums. We now have, through John Delaney of the University of Washington, a very nice set of water-bearing obsidian standards which were done by the ion probe and by the

microprobe. What we get by those methods are right on what they should be. Those things had high water concentrations, and I have closed my mind to that.

Kienle: I'd like to know how Bill Melson, on the one hand, and Steve Malone, on the other hand, can resolve the discrepancy between the concentration of most of the earthquakes very shallow in the edifice, on the one hand, and 15 km depth overpressures on the other hand.

Melson: It presumably had a standing magma column which slowly was moving into place before even the first seismic shocks. That's how I would look at it. It was there already and slowly oozing up and its pressure probably getting more-and-more, larger-and-larger relative to the static pressure, the overpressures increasing. So the system starting cracking, and that's when you had all the shallow earthquakes. Then, when it blew, the root became active because more magma started intruding into the deep plumbing system, which meanwhile was sitting there more as a plug with no motion to speak of. That 20 kilometers is a nice figure to get the kind of pressure to keep the water in.

Malone: So you view that as a magma column rather than a magma chamber?

Melson: A magma column or a "magma bead" possibly. As a magma chamber, I don't know. I think that's where the seismology really has to help. I don't know that petrologically we can tell. One thing I didn't get into is that there are microcycles in water concentration (Figure 8). By June 12, water concentration, according to many samples, had dropped and then went up again at a smaller scale. So, rather than seeing that drop like I showed in Figure 8, it was oscillating. It looks to me like the magma body was being replenished by water- rich magma and that we might have tapped even more than one magma chamber. It is not easy to explain, but the water concentration is not a smooth linear decrease. There was water-rich and then somewhat water-poor magma alternating in the system.

Malone: That's interesting because we saw a strong tremor up through or about the middle of June, not really after that -- other than just before and during some eruptions. Up through or about the June 5, or even a little later than that, there was a strong, what we call a deep type of tremor often associated with an eruption, but nothing since then.

Peterson: Do you have any thoughts on what the magma was doing prior to March 20? How long did it take to get in place? Obviously, we see the manifestation of the implacement beginning March 27, but does your chemical analyses provide any insight into what was happening before?

Melson: I think there are three possibilities: one, that without seismic signature the volcano had slowly inflated or the seismic signatures were so infrequent that nobody was alarmed about it. Maybe Steve could talk about that. By the time the seismicity got significant, the system was already inflated. The other possibility is that the magma, left over from the last century, as perhaps part of the old cryptodome, was slowly crystallizing before it started moving. And as it did so, what little water that was left caused the water pressure to increase -- the old second boiling model. It began to exert its own pressure and caused the failure which then opened the deep system to replenishment, thereby causing the deeper earthquakes. So, the one model is that new stuff was slowly oozing and inflating it, and the other is that the initial event was related to the crystallization of older magma. The third case is that the whole thing was seismically and tectonically controlled. When we see that many great linear earthquake belts moving through there afterwards, there is a suspicion that the tectonics were also very much active and perhaps triggering either of the previous two models.

Question: Would you care to comment on the difference in color between the dark

vertical blast and the whiter horizontal blast in the May 18 eruption?

Melson: The contrast in the color? You mean the first, the black phreatic plume? Basically, to me, most of that was phreatic, and I would assume the black was an andecitic mass that was being fractured and blown to pieces. The white was a lot of steam, part of it condensing. And a lot of the white later on, but not at that particular time, was pumiceous. As far as I can see, during that initial avalanche phase and shortly thereafter, there was primary liquid coming out, primary magma, some of which was white and pumiceous. But it was a relatively small percentage compared to what came out a few hours later.

Session Chairman: Decker: Thank you, Bill. Are there any additional questions for Steve Malone?

Question: Have you made any P-wave delay studies on Mount St. Helens?

Malone: There is one now going on. In fact, it includes a lot of Washington. All the stations in our network are being used in it. One of our students, Carol Michaelson, is working on that, and she is giving a paper on it next week at the AGU. Most of her work so far has been over the whole state, not specifically at Mount St. Helens. You have to do that before you look at the local details because you have to account for the regional data first. At first glance, there isn't anything that stands out very sharply at Mount St. Helens, nothing like some of what has been seen under either Long Valley or the Clear Lake area. It is still a bit early in that study to draw conclusions.

Question: I was under the impression that you were in search of an earthquake when the one happened at Mount St. Helens. Suppose you had had an earthquake that diverted your attention the day before, say a magnitude 6 earthquake at the Okanogan Valley. How long would it have taken someone to recognize that something strange was going on at Mount St. Helens?

Malone: Yeah! (Laughter) A magnitude 6 is pretty big. That would have diverted a lot of attention. Well, it varies, of course, at different institutions and under different conditions. At that time, because Mount St. Helens is a volcano, and based upon lots of other work, it was a suspicious volcano, I think as soon as a sizable quake had been located there, we would have had an eye on it.

That has occurred at other volcanoes too, an isolated event when nothing materialized afterwards, as that single first earthquake did. It didn't immediately stir up a feeling that "something really terrible is happening." Rather, it was, "Heh, let's watch that a bit more." We would probably not have put in the additional stations when we did had it not been convenient. But probably within two days we would have still gone ahead because the rate of activity obviously did increase during that period of time.

The scary sort of thing I dread is the story like we just heard of just a two-day precursor. I gather that at Arenal, there weren't seismographs right there. Is that correct? These were felt earthquakes in the two days at Arenal? Perhaps there had been smaller events that had preceded those two days. One can always hope that will be the situation, that your instruments will tell you before the local inhabitants. That's embarassing when they tell you before your instruments have.

Kienle: In California, where there is so much seismic background compared to Washington, do you believe the extra effort toward discriminating volcanic earthquakes and tectonic earthquakes should be required?

Malone: Well, I think a good example is the Stephens Pass example. There, I think, within just a couple of days, there was additional instrumentation in there. And, I think it is a good example where having a number of different institutions that are

potentially interested and willing to make the effort is important.

REFERENCES CITED

Anderson, A.T., 1975, Water in some hypersthenic magmas: Journal of Geology 87, p. 509-531.

Fudali, R.F., and Melson, W.G., 1972, Ejecta velocities, magma chamber pressure and kinetic energy associated with the 1968 eruption of Arenal Volcano: Bulletin Volcanologique, v. 35, p. 383-401.

Lipman, P., Norton, D.R., Taggart, S.E., Brandt, and Engelman, E.E., 1981, Compositional variations in 1980 magmatic deposits, in The 1980 eruptions of Mount St. Helens, U.S. Geological Survey Professional Papers 1250, p. 631-640.

Malawassi, E., 1979, Geology and petrology of Arenal Volcano, Costa Rica: M.S. Thesis, University of Hawaii at Manoa.

McBirney, 1982, Realistic volcanic hazards assessment: The importance of explosivity/frequency relations, in this volume.

Melson, W.G., Jarosewich, E., Switzer, G., and Thompson, G., 1972, Basaltic nuées ardentes of the 1970 eruption of Ulawun Volcano, New Britain, Smithsonian Contributions Earth Science, v. o, p. 15-32.

Melson, W.G., and Saenz, R., 1973, Volume, energy and cyclicity of the eruptions of Arenal Volcano, Costa Rica: Bulletin Volcanologique, v. 37, p. 416-437.

Moore, J.G., and Melson, W.G., 1969, Nuées ardentes of the 1968 eruption of Mayon Volcano, Philippines: Bulletin Volcanologique, v. 33, p. 600-620.

ADDITIONAL GEOPHYSICAL TECHNIQUES FOR MONITORING VOLCANOES: GEODETIC, GRAVITY, THERMAL, ELECTRICAL, MAGNETIC, AND RADIOACTIVITY

Robert W. Decker, Scientist-in-Charge
Hawaiian Volcano Observatory
U.S. Geological Survey

ABSTRACT

Seismic techniques are the most important geophysical monitors of active volcanoes. Following seismicity, other geophysical techniques, listed in order of their present importance, are: geodetic, gravity, thermal, electrical, magnetic, and radioactivity techniques. Geodetic measurements of tilt, elevation, and horizontal-distance changes are extremely valuable on Hawaiian volcanoes and on Mount St. Helens. Intermittent field surveys, in combination with a few continuous monitors, provide useful deformation data in both space and time. These data aid in understanding the geometry of subsurface magma movements, as well as yielding useful forecasting information. Elevation changes of several centimeters and subsurface changes in density, which can be monitored by sensitive gravity meters with accuracies of about ten microgals, form an important complement to geodetic techniques. Temperature changes in crater lakes and gas vents, caused by convection of ground water or mass transfer of magma or volcanic gases, give insight into thermodynamic changes at depths down to a few kilometers. Conductive heat-flow processes are much slower and less important in the short term. Molten rock has low electrical resistivity and is nonmagnetic. Cooled lava has high electrical resistivity and is weakly magnetic. Thus, electrical, magnetic, and electromagnetic surveys can potentially detect the configuration of and changes in the geometry of subsurface magma bodies. Changes in radon gas concentration near the surface of volcanoes yield information on changes in subsurface stresses and permeability. The primary goal of geophysical monitoring of volcanoes is to understand their structure and dynamics. Empirical forecasting of eruptions without an understanding of the basic processes involved is a precarious substitute.

INTRODUCTION

If I were given only one instrument to monitor a volcano, I would choose a seismometer. Given two instruments, it would be a seismometer and a device to measure surface deformation. This would differ according to conditions; a tiltmeter for small displacement and aerial photography for large displacements such as that at Mount St. Helens (200 m). For monitoring volcanoes, a team approach is best: a geologist to say what did happen; a geophysicist and geochemist to say what is happening; and, a lobbyist to go to Washington to say what might happen! Many organizations can be involved in such efforts, but they must talk with each other. Progress in understanding a volcano's behavior is best achieved by a multidisciplinal group of earth scientists working together.

Much of the following information is based upon research on the Hawaiian volcanoes. These basaltic volcanoes are frequently contrasted with more silicic volcanoes which are regarded as less predictable and more explosive in nature. In Hawaii, pyroclastics make up only about one percent of the total erupted materials, but it is that

one percent that really worries us. Hawaiian volcanoes are not entirely benign. The volcanic eruption in 1790 would have destroyed our volcano observatory had it been there. These strong eruptions recur at 1,000-2,000-year intervals. It takes a few hundred years to learn to anticipate eruptions, and I believe we are making good progress in Hawaii.

History of deformation observations on volcanoes dates back to the second century before Christ. At Pozzouli, on the north shore of the Bay of Naples, a 2,000-year record of subsidence followed by uplift (Figure 1) is preserved by borings of marine mollusca in columns of the Roman Temple of Serapio (Flemming, (1970). The submergence amounted to six meters in ten centuries. Perhaps the AD 79 eruption of Vesuvius had something to do with it, even though Vesuvius is some ten kilometers away on the south side of the Bay. The Bay of Naples is a large volcanic system, and Vesuvius is only one of the parts. Subsidence of the temple continued until 800 or 900 AD, then movement reversed. In 1538, an eruption in the country west of Naples created the volcano, Monte Nuovo. Eye witnesses saw more rapid uplift of the bay shore, then subsidence following the eruption (Pichler, 1970). Most recently there has been uplift, but, at present, there is no movement. The center of the movement since 1970 (Casertano and others, 1976) is the city of Pozzuoli.

DEFORMATION MONITORING

Generally, four types of deformation measurements are used on volcanoes. Classical leveling is accurate to one to ten millimeters of vertical movement per kilometer of horizontal distance. Watertube tiltmeters, on three piers 50 meters apart, can measure one part in 10^7 of tilt but this is rather tedious and must be measured at night to minimize errors caused by solar heating of the installation. Dry tilt is a simple process, done by resurveying a triangle of ground points (benchmarks), with an optical level. One must shade by umbrella the prism-type level measuring instrument. This is accurate to one microradian, or one part in 10^6 (a one-kilometer line tilting one mm). Distance measurement of horizontal stretching of a volcano is done with a geodimeter or other electronic distance measurement instrument; one part in 10^5 is the expected accuracy.

In Hawaii, we typically experience changes in surface tilt of one part in 10^4 occurring in movements over periods of days if the volcano is deflating or erupting, or over periods of months to years if inflating, so dry tilt and geodetic measurements are adequate. More subtle movements can be measured by more sensitive methods such as two-wave length geodimeters. For movements of tens to hundreds of meters, aerial photography and photogrammetry is applicable.

Kilauea caldera has an outer rim about 4 km x 3 km; uplift is measured in centimeters but totaled one meter in 1960-1961 -- the uplift was symetrical (Figure 2) and ignored the major fracture system. If deformation is less than two meters, uplift or subsidence acts in an elastic manner over a bulge ten kilometers across. If vertical deformation is two meters or more, major movement on border faults commonly occur. Major removal of magma from the chamber results in collapse along the faults. By measuring variations of line lengths across the caldera, we get vectors that represent displacement. It inflates like a balloon. In July-September 1975, there was uplift of the volcano by one-half meter, and displacement was outward radially from the zone of uplift.

TILT HISTORY AT KILAUEA

A history of inflation and deflation at Kilauea from the mid-1950s to 1980 is shown by the graph (Figure 3). Eruptions and eruption periods are indicated on the bar at the top. In 1959 and 1961, summit eruptions and flank eruptions followed periods of slow inflation. The entire graph shows a history of slow inflations and rapid deflations as if the volcano were breathing. Each eruption starts as an intrusion, though all intrusions don't progress to the eruption stage. High inflation increases the likelihood of eruption, but we have not identified a critical stage that signals eruption.

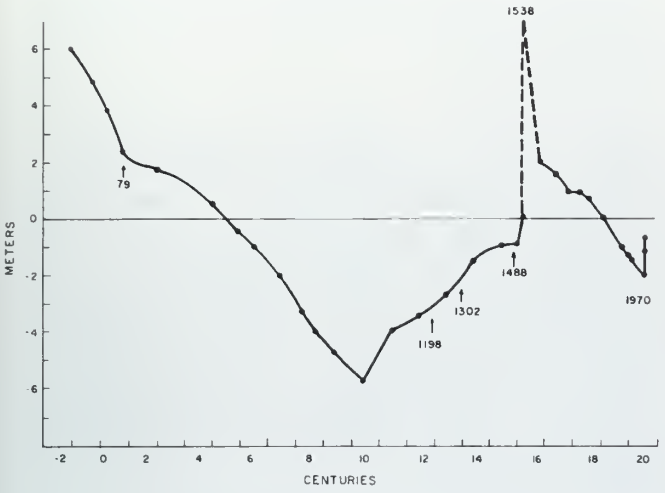


Figure 1. A 2,000-year record of subsidence, rebound, and subsidence of the coastline at Pozzuoli, Italy, and its relation to volcanic eruptions at Vesuvius and Monte Nuovo volcanoes. Data from Pichler (1970) and Grindley (1976).

Figure 2. Near symetrical inflation at Kilauea caldera during 1960-61. The uplift figures are in centimeters.

In the Mauna Ulu eruptions starting in 1970 (Figure 3), the volcano actually inflated over the long term while eruption was going on -- a different situation than before. Lava of low viscosity and gas content was erupted. From 1971 through 1975, the Mauna Ulu crater and flank eruptions continued. The tilt capacity increased which implies a stronger volcano that could withstand more pressure before breakdown. In 1975, there was a major M 7.2 earthquake that let large-scale deflation take place. One-hundred million cubic meters of magma moved out as more room was created underground. Part of the stress was relieved by gravitational slumping which took place on the free (ocean) side of the volcano. The submarine slumping and interior magma pressures on the east rift zone and southwest rift zone produced a push-pull effect that resulted in sudden catastrophic failure of the south flank of the volcano. In 1975, the behavior changed: prior to 1975, there had been ten eruptions and three intrusions; since then, there have been two eruptions and 14 intrusions. An observatory needs to run quite awhile to get evidence for what is going on in the subsurface.

FINDINGS

Figure 4 is a histogram showing the total number of weeks and the level at which inflation stood at the beginning of each week. By comparing the ratio of tilt occurring in weeks in which eruptions began to the more average level of tilt for weeks in which eruptions didn't begin (Figure 5), we get an increase in the probability of eruption based on amplitude of inflation. This is then compared to average probability, which is 2-1/2% for any given week, given no other information.

To understand the theoretical structure and dynamics of the system, we ask: What would the surface do if this model is correct? We match that with the observations to test it. At Kilauea, deformation appears to be controlled by magma pressure at a depth of about 3 km. A shallow storage reservoir exists at that depth. There is not a simple point source or sphere at that depth, rather, there is migration of the apex of inflation. In general, eruptions start when the center of inflation is in the south, as contrasted to the north, but there have been exceptions.

The degree of inflation now is similar to what it was in 1968 when there was a year-long eruption of the Halemaumau vent. It was higher prior to the 1975 earthquake. The caldera diameter up to 1975 behaved in a similar manner. Since the earthquake, however, the diameter has continued stretching while vertical displacements have decreased. It is not behaving in an elastic manner. Subsidence apparently is mainly by gravity; there is no horizontal restoring force.

The goal of society in these studies is to forecast the activity while the scientific goal is to understand the structure and dynamics of the individual volcano. Forecasting should depend on the latter, rather than on an empirical monitoring formula. The present model shows a deep source with magma rising more or less continuously to a shallow magma chamber, dilating the surface of the volcano until it reaches a critical point, then fracture occurs in the rift zones, or even the summit, causing an eruption or intrusion. This can be compared to the electrical circuit of a relaxation oscilator or "highway flasher" in which a battery supplies current through a resistor to slowly charge a condenser, until the critical firing voltage of the associated neon lamp is reached. The lamp flashes, discharging the condenser, and the process starts over again. In the volcano, a deep magma source is a battery; the conduits are a resistor; the shallow magma chamber is a capacitor; and, failure to the surface or intrusion is like a neon bulb. The main difference is that the relaxation oscilator is very regular in frequency; whereas, the volcano is not. This infers a variability in the component parts, the easiest of which to change is the strength of the volcano before eruption.

DEFORMATION STUDIES ON OTHER VOLCANOES

Mauna Loa. A geodetic network established at Mauna Loa in the mid-1960s

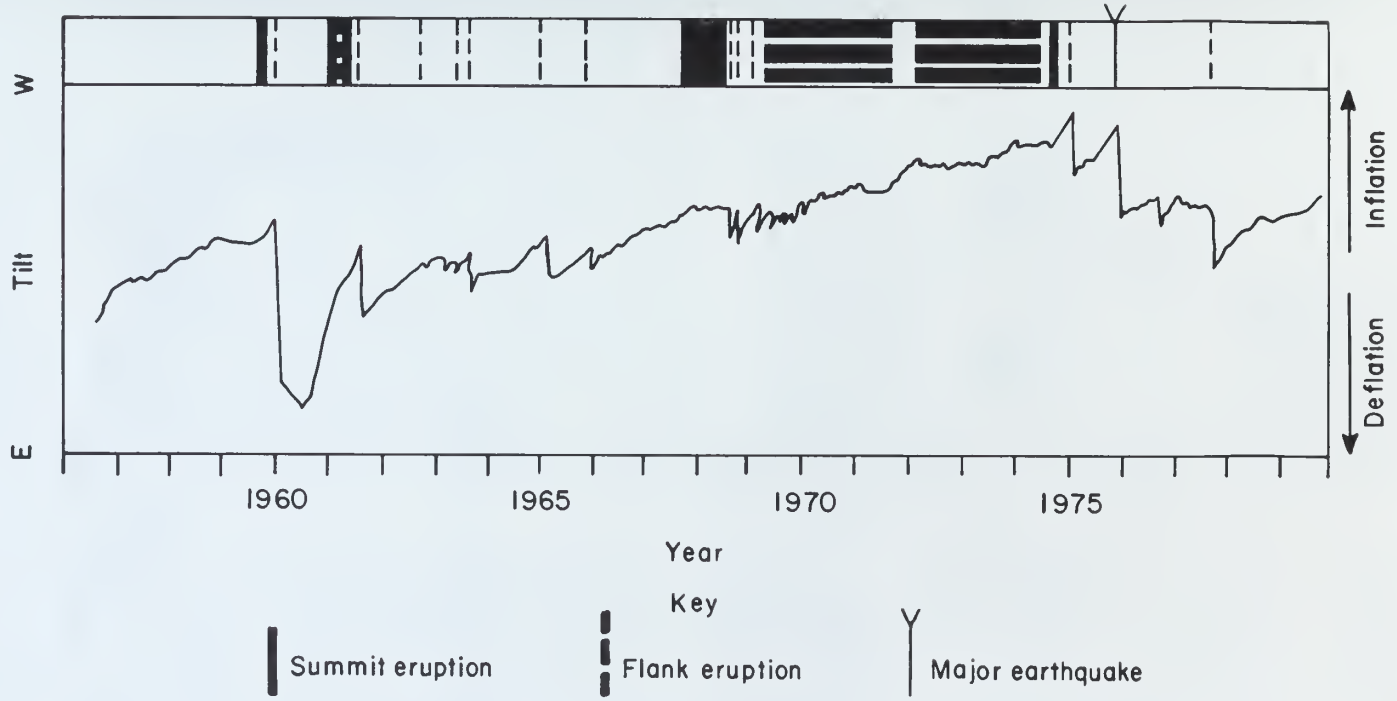


Figure 3. Radial tilt from Kilauea Caldera measured at the Hawaiian Volcano Observatory from 1956 to 1980 (from U. S. Geological Survey, Hawaiian Volcano Observatory summaries). For months to years before an eruption, the summit of Kilauea inflates. When it reaches a level that exceeds the strength of the rocks surrounding the shallow magma chamber, the volcano erupts. Removal of large volumes of magma from the summit chamber causes the volcano to deflate over a period of days. A high level of inflation indicates a higher probability of eruption, but since the strength of the rocks surrounding the magma chamber varies from one eruption to another, no exact level of tilt can be used to predict the next eruption.

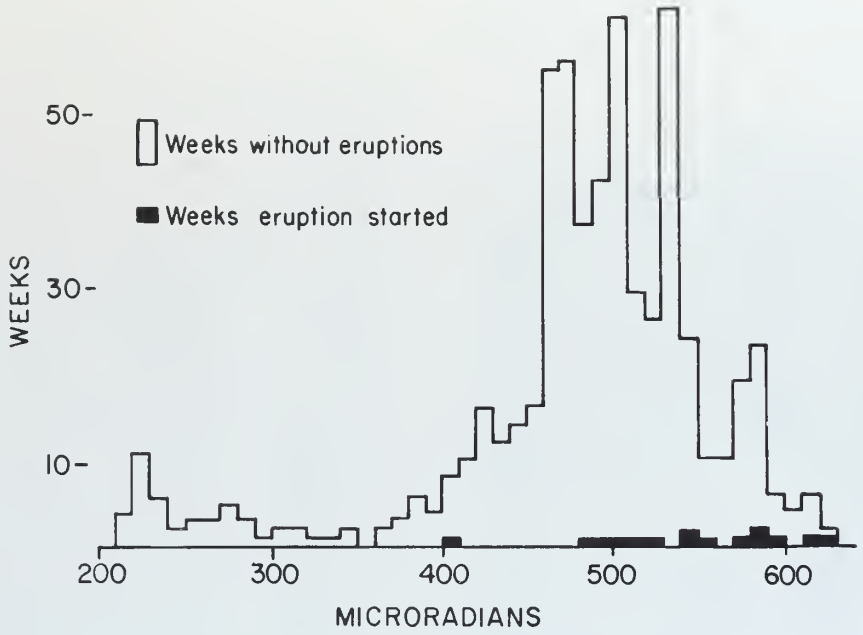


Figure 4. Histogram of the number of weeks during which radial tilt stood at certain microradian levels on Kilauea Volcano, Hawaii, 1956-1969. The tilt levels during weeks in which eruptions started are shown in black near the horizontal baseline.

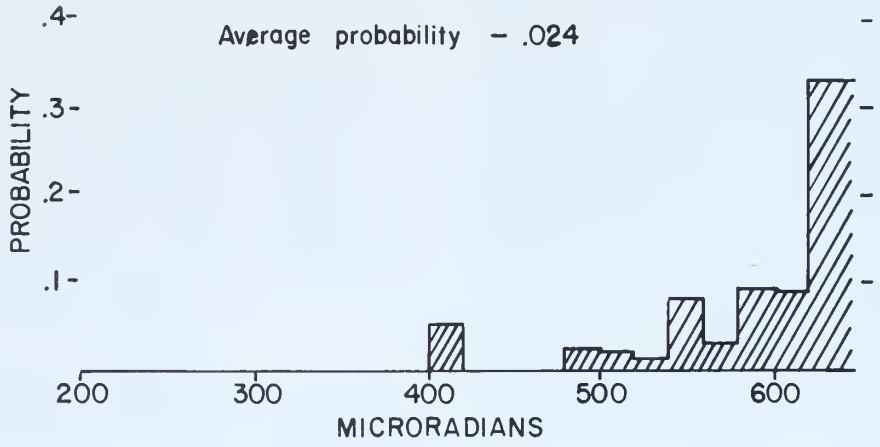


Figure 5. The ratios of weeks with and without eruptions from Figure 4 give the probability of seeing the start of a new eruption of Kilauea during a one-week visit to Hawaii during the period 1956 to 1969. As the radial tilt increases, so does the probability of an eruption.

was a simple one with one distance measurement across the summit and a large level triangle as a tiltmeter. Early measurements showed little or no activity. The system was expended and refined, and in 1974 began to show displacement. The caldera began to stretch apart and increased radial tilts were measured. However, earthquake activity beneath the summit increased, and this was the real indicator of a coming eruption. A sudden change in seismicity occurred about nine months before the eruption in 1975.

Today, no one is near predicting precisely the day of eruption, but indications like those now observed at Mauna Loa should make one more alert that something might take place. Deformation has continued at the summit since the 1975 eruption. This has been modeled to show a center of inflation which is just southeast of the main caldera. It has a calculated depth of about 5 km, and the volume added since 1975 is 100 million cubic meters. The volcano is swelling, not as rapidly as Kilauea, but it is not dead like it was between 1965 and 1974.

On Soufiere Volcano, St. Vincent, tilt stations 2-3 km from the summit and 5-6 km from the summit were installed before the April-May 1979 explosive eruption. They showed inflationary trends leading up to the eruption. At Mount St. Helens, the bulge was detected visually and was also measured starting in mid-April 1980. Barry Voigt (1981) of Penn State University made the best short-range forecast. He looked at the size of the slope that might fail and predicted it might be in the billion-ton range. As to the mechanism starting that eruption, I agree with Malone (1981) that the landslide triggered by the earthquake unleashed the hydromagmatic eruption. However, I also agree with Melson (1981) that it was the magma moving under great over-pressure depth to a shallower holding chamber that accounted for the earthquake. This argument over whether the eruption was triggered by the earthquake, or the earthquake was caused by the eruption, is a chicken-versus-the-egg type of situation.

Deformation measurement has been very useful in a forecasting sense at Mount St. Helens, with a forecast period of a few days to a few weeks. Deformation preceded the May 19 eruption by 53 days. Deformation was detected four days before the October eruption. Don Swanson's work (1981) has shown that you get ten days to two weeks warning as the deformation occurs before an eruption, as compared to hours or days warning from seismic precursors.

OTHER GEOPHYSICAL TECHNIQUES

Gravity is a geodetic technique. It can determine isostatic imbalance, and gravity meters can also be employed for measuring elevation changes. (As you get farther away from the earth, you weigh less.) Gravity meters are so sensitive today that elevation differences of 10 cm can be measured, and these are not subject to cumulative errors, as are geodetic level lines. This is one of the best reconnaissance techniques.

Temperature monitoring. Neuman Van Padang in Indonesia spent much of his life measuring temperatures of fumeroles. He wrote a paper (1963) after an eruptive phenomenon. However, in special situations like a summit crater lake, increases in temperature of the lake may signal forthcoming eruptions. Such observations were recorded at Taal Volcano's crater lake (Alcaraz, 1969), but just the opposite relation has been observed at Ruapehu in New Zealand. Apparently, at Ruapehu, the crater lake remains warm when the volcanic system remains open, but dangerous conditions exist when the volcanic system is closed and the lake cools. This cooling of the lake has been observed to precede eruptions by as much as a year or two. At the moment, the lake is cold.

Magnetic anomalies. These, too, have been recorded on Ruapehu. They show changes in the magnetic field of 10-15 gammas, which clearly precede eruptions in some instances by hours to days (Johnson and Stacy, 1969). The phenomenon is not well understood, but may be due to piezomagnetic effect, temperature, or rapid changes in electric properties of the volcano.

Self-potential can also be used. In Hawaii, it has been found that if you put electrodes in the ground, particularly on

opposite sides of the rift zone, a potential of as much as one volt may be detected. This may be caused by ground water movement downward, causing a streaming potential. If a thermal anomaly blocks downward percolation of water, this can superimpose a changing, opposite voltage. Intrusions on the rift zones have been detected in that way.

Radon measurements have been investigated as a forecasting method, but although there have been changes or increases leading up to volcanic events, there does not appear to be a clean-cut correlation. Radon gas emission may be more related to permeability changes due to seismicity or stress release, or to inflation, rather than directly to magma proximity.

FORECASTING FACTOR AT KILAUEA

Fred Kline is presently working on probability factors of eruptive activity at Kilauea. The normal weekly probability of eruption is two and one-half percent, providing the volcano is not presently erupting. Inflation amplitude, inflation rate, the number of summit earthquakes that are occurring, and the fortnightly tide are four empirical factors that are put together to give a "tip" to its likely behavior. In June 1981, the probability of eruption was enhanced by a factor of two or three. There was no eruption, but there was a major intrusion in August. A body of molten material was injected along the rift zone for 18 km. It was calculated to be 4 km high, about a meter wide, and as shallow as about 250 meters from the surface. Earthquakes indicated a stress zone around it. Intrusion of the body occurred at a rate of 2 km per hour at first, but later slowed to 1/2 km per hour. The southwest rift zone inflated, and the summit deflated. The tilt has now recovered about 60% of what it lost in August 1981. About 40 million cubic meters were lost and recovery has been very rapid. This rapid inflation of Kilauea looks very promising for more volcanic activity in 1982.

In summary, we think we can now infer what is happening in a structural and dynamic way in the subsurface, and from what we learn from this, we hope to refine our techniques to come up with forecasts that are more accurate than we have at the moment.

DISCUSSION

Question: Have you ever tried any repeat magneto telluric measurements?

Decker: Electro magnetic measurements that are being done are a controlled source conductivity experiment and not the classic magneto tellurics done by Hermantz and others.

Question: Could MT pick up evidence of shallow magma emplacement before seismicity begins to show up?

Decker: That is possible. My own interpretation is that the movement of magma from a holding chamber 15 km down began about the same time as the seismicity began -- I am of the opinion that the action at Mount St. Helens started on March 20 and not much before.

Question: Why is the center of inflation at Kilauea off the center of the caldera, and would you care to relate that to the fact that the bulge at Mount St. Helens was off center also.

Decker: I will try to answer that in two parts. At Kilauea we don't envision the shallow magma chamber as a sphere or a vertical cylinder or any simple geometric feature. It is probably a plexus of sills and dikes and apophyses, perhaps, like a Mickey Mouse balloon. First the head blows up, then one ear, and so on. If you look at the area of the caldera, you probably see the areal dimension of that plexus down below. But what particular part of that plexus may be inflating at any one moment, perhaps, changes with time. With regard to the offset nature of the earthquakes and the bulge: it is possible that the holding chamber might have been fairly axial to Mount St. Helens, but the failure was only

on one side, so that would bias the earthquakes in the side that was failing and also bias the deformation bulge to the side that was failing. In short, the intrusion was possibly symmetric but the strength of the rocks was asymmetric.

Question: If you have rising magma causing updoming, how would you use gravity as a measurement of elevation changes?

Decker: In Hawaii, it has been found that there have been gravity changes which are greater than the anticipated free air or Bouger change, with a nominal change in elevation, and also changes which are less than that. However, in all cases, when there has been uplift and that uplift is accompanied by a change in density in the subsurface, there have been measurable gravity changes. So, as a reconnaissiance tool, I would say that the gravity would have shown a change even though it might not be a one-to-one elevation change in a Bouger or free air gravity reduction. On the other hand, if one can afford to do both an elevation survey by leveling and a gravity survey, you can separate the elevation effect from the mass-change effect, and that gives you information which you can't get any other way.

Question: How do you estimate the volume of magma that is moving but never comes to the surface?

Decker: The collapses which show these rather rapid subsidences of the summit of Kilauea have been looked at by many techniques: in one case you can do a modeling study. Knowing how much tilt has been changed, you assume where the apex of that deflation took place and use a straight-forward elastic model to come up with a volume change in that model. This has been corroborated with detailed level surveys. This has been done, perhaps, eight or nine times at Kilauea, and always the level survey shows a volume of subsidence that is within, say, 10% to 20% of the amount calculated from an elastic model. There is, of course, the assumption there that the volume of collapse is equal to the amount of removal of magma from the magma chamber, and this assumes that it is a very low strength type of thing. If, on the other hand, the volcano had a very high strength, then, the amount of surface deformation would be a lot less than the volume intruded because it would be accommodated by elastic compression in the edifice itself. We believe that the summit of the mountain is so broken up and blocky that it has the strength of a sandbox rather than a laboratory piece of basalt.

McBirney: Many of the methods that have been developed at Kilauea we thought would never be applicable on andesitic volcanoes. Tilt and harmonic tremor observations at Mount St. Helens are now turning out to be quite useful. Would you be willing to predict or speculate on what we should be doing on andesitic volcanoes in light of your experience on Kilauea?

Decker: I think we should be doing many of the same things we are doing at Kilauea to the andesitic volcanoes. I think one group, or a multiple of groups, should look at 10 or 20 volcanoes at the same time, rather than one, because the period of repose is such that you are going to have to maintain your attention span for more than one generation. I think Hawaii is a place because you can maintain your attention span in one generation, but, I agree, I am amazed as well how some of these techniques have been very useful in other parts of the world. I guess Pozzuoli should have tipped us off to that.

Melson: The big difference is the response time. I've noticed this in the tilt measurements made at Arenal. The response time is slower for andesitic and dacitic magmas because they are more viscous so they take a longer time, even within an eruptive cycle, to effect surface movements.

Decker: This is why I suggest that a group should look at 10 or 20 volcanoes. What I was talking about is really only observational monitoring of a volcano. It can be used both in a forecasting sense and a

modeling sense, but, in between observations, I think one should be constructing theoretical models, trying to figure out experiments to test those models, and also trying to figure out what additional observations you need to test these theoretical models.

Question: Would you explain the dry tiltmeter, please?

Decker: It is a triangle of piers, or benchmarks, in which you do precision leveling. You set up a level gun in the middle and turn from one pier to the next to measure their elevations with respect to one another. You come back a few weeks later and do the same thing to find out if their elevations with respect to one another have changed. As long as you have a triangle, it will give you not only the magnitude but the azimuth of the tilt of that particular block of ground between those three piers.

Question: Have you gone public with your eruption factor forecasting information in Hawaii?

Decker: Yes and no. We have certainly been releasing it to the National Parks Service. We have been releasing it to the civil defense, and we have been publishing it in the monthly report. We really haven't started to send it out to the newspapers on a weekly basis or anything like that because we have only tested it for a year, although you can run it in hindsight in twenty years' data. That is how you come with this thing. I guess we are not quite courageous enough yet to go public with it because I don't think we have the public, even in Hawaii, appreciating the fact that, perhaps, the best you can do at this time is a "probabilistic" type of forecast. We think we can do much better than guessing, but we are so far from being precisely "deterministic" that we feel that our "glitches" are going to be much more well-remembered than our successes.

Question: Was the inferred depth to the magma chamber at Long Valley calculated from the geometry of the bulge?

Bailey: There have been some calculations that would place the magma chamber about 11 km beneath the center of inflation. The 8 km figure was derived from seismic refraction studies by Dave Hill, published in 1976.

REFERENCES

Alcaraz, A., 1969, Is Taal Volcano drawing closer to another eruptive activity? Comvol Letter, Philippine Committee on Volcanology, v. 3, n. 5, p. 1-10.

Casertano, L., Oliveri Del Castillo, A., and Quagliariello, M.T., 1976, Hydrodynamics and geodynamics of the Phlegraean Fields area of Italy: Nature, v. 264, p. 161-164.

Decker, R.W., 1974, State of the art in volcano forecasting: Bulletin Volcanologique, v. 37, p. 372-393.

Decker, R.W. and Kinoshita, W.T, 1972, Geodetic measurements: UNESCO Earth Science Series, n. 8., p. 47-72.

Fiske, R.S. and Kinoshita, W.T., 1969, Inflation of Kilauea Volcano prior to its 1967-1968 eruption: Science 165, p. 134-139.

Flemming, N.C., 1970, Archaeological evidence for eustatic change of sea level and earth movements in the Western Mediterranean during the last 2,000 years: Geological Society of America, Special Paper 109.

Grindley, George W., 1976, Relation of volcanism to earth movements, Bay of Naples, Italy, in Gonzales Ferran, editor, Proceedings of Symposium on Andean and Antarctic Volcanology Santiago 1974: Internal Association of Volcanology and Chemistry Earths Interior, Special Series.

Hill, David P., 1976, Structure of Long Valley caldera, California, from a seismic refraction experiment: Journal of Geophysical Research, v 81, p. 745-753.

Johnson, M.J.S. and F.D. Stacy, 1969, Transient magnetic anomalies accompanying volcanic eruptions in New Zealand: Nature, v. 224, p. 1289-1290.

Newman Van Padang, M., 1963, The temperatures in the crater region of some Indonesian volcanoes before the eruption: Bulletin Volcanologique 26, p. 319-336.

Oliveri Del Castillo, A. and Quagliariello, M.T., 1969, Sulla genesi del bradisismo flegreo. Atti Ass. Geof. It., XVIII Conv. Naples, 38 p.

Pichler, H., 1970, Italienische Vulkan - Gebiete II: Sammlung Geologischer Fuhrer, Band 51, Gebruder Borntraeger, Berlin, 186 p.

Swanson, Don A., Lipman, P.W., Moore, J.G., Heliker, C.C., and Yamashita, K.M., 1981, Geodetic monitoring after the May 18 eruption, in Lipman, P., and Mullineaux, D., editors, The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 157-168.

Voight, Barry, 1981, Time Scale for the first moments of the May 18 eruption, in Lipman, P., and Mullineaux, D., editors, The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 69-92.

THERMAL INFRARED IMAGERY OF THE CASCADE RANGE VOLCANICS

Dr. I. William Ginsberg
Aerial Measurements Operations, EG&G, Inc.
Department of Energy Remote Sensing Laboratory
Las Vegas, Nevada

As prime contractor for the Department of Energy's Remote Sensing Lab in Las Vegas, we perform all of the remote sensing tasks for the U.S. Department of Energy (DOE) as well as those of other federal agencies. We are designated as one of the emergency response laboratories of the federal government. In March we were asked by the U.S. Geological Survey to provide some aerial remote sensing, particularly thermal infrared, over Mount St. Helens. After a few successive flights, we were asked by the U.S. Geological Survey to perform an extensive survey of all the Cascade Volcanoes from Washington to northern California. We completed that survey in August.

The equipment used in these flights is a multispectral scanner, manufactured by Daedalus. As the aircraft moves along, radiant energy is picked up by a rapidly rotating mirror, recording a transverse swath of terrain. The mirror transmits it as an optical beam to an infrared detector, which changes it from an optical to an electronic phase. The electronic signal can then be converted into an image. The images called for represent radiant infrared energy of 8.5 to 13.5 microns wavelength. This is essentially heat energy which is invisible to all photographic films.

Under it's prime contract with DOE and with support from the U.S. Geological survey, EG&G has conducted three remote sensing missions at Mount St. Helens volcano in Washington State. In March, we got some infrared data, but had a failure in the scanner prior to our pre-dawn mission. We flew a noontime mission, but because of possible solar effects, there were some questions as to what the data meant. We also flew Mount St. Helens in March and April; in May, the Friday before the May 18 eruption; and in July of 1980.

Figure 1 is a vertical aerial photo of the summit of Mount St. Helens on May 16, 1980, before the catastrophic eruption. The dark areas on the photograph are ash covered snow and ice fields, except in the crater area near the center, while the lighter areas are exposed snow and ice. North is on the left.

Figure 2 displays before and after thermal images of the summit. The left image was acquired in the predawn during the 16 May 1980 mission (two days before the first major eruption). The vertical aerial photograph (Figure 1) was acquired the same day near solar noon. The scale of the imagery and photography is approximately 1" = 1,000' and north is on the left in both cases. The right image was acquired on August 20, 1980.

The apparent temperatures represented on the infrared image range from -10°C to 25.5°C. The lower 6.5°C of this range are ambient temperatures, and are shown in black and white tones. The upper 29°C of the range are temperatures which are greater than ambient and are best shown in color enhancements. Because Figure 2 is a black and white rendition of the original color enhancement, the temperature is partly reversed in relation to the image gray scale.

The oval area in the center of the thermal image and the photograph is the crater. Steam and/or gas escaping from vents on the east and north sides are indicated on the thermal image by the colored areas. These

Figure 1

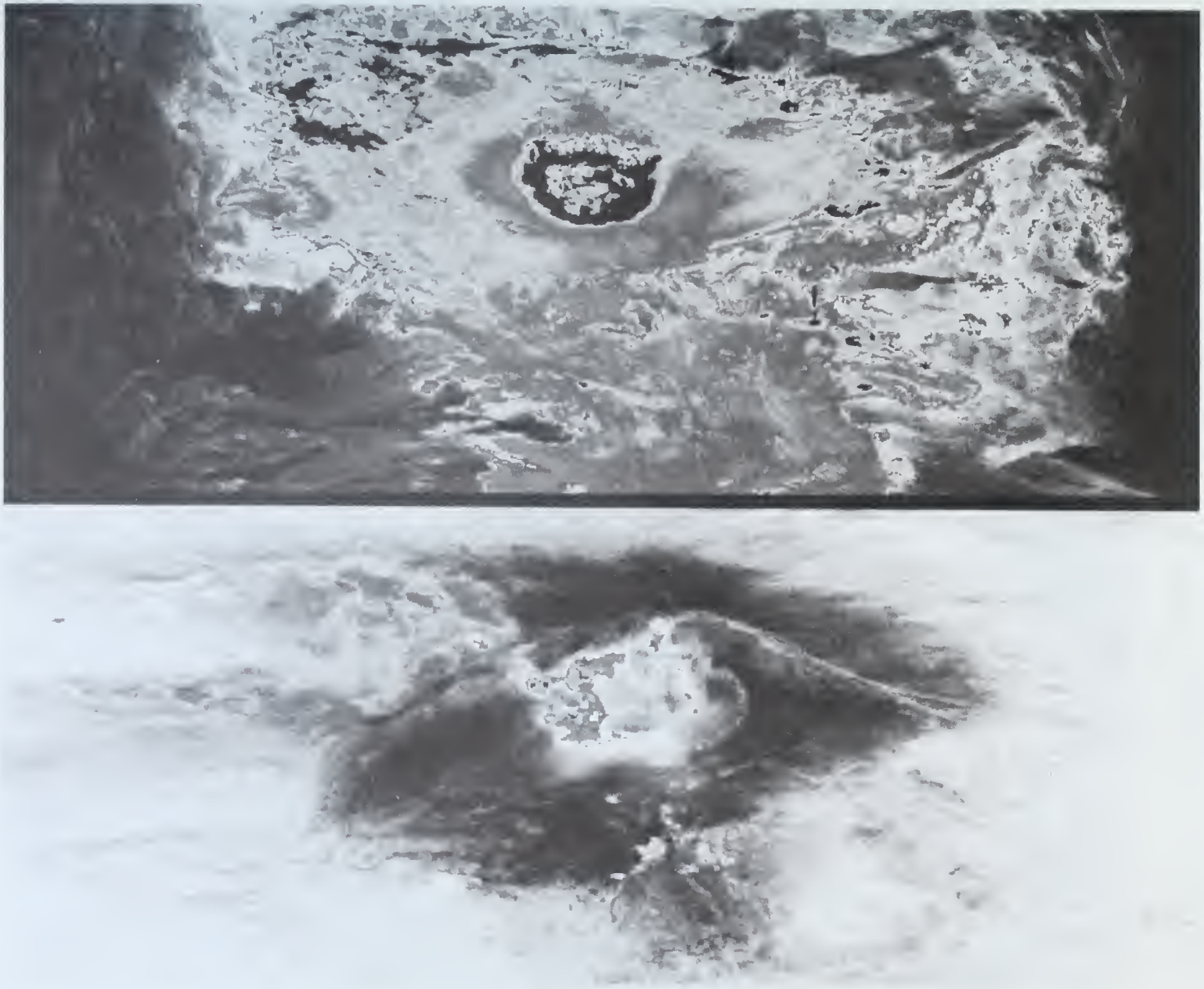


Figure 2

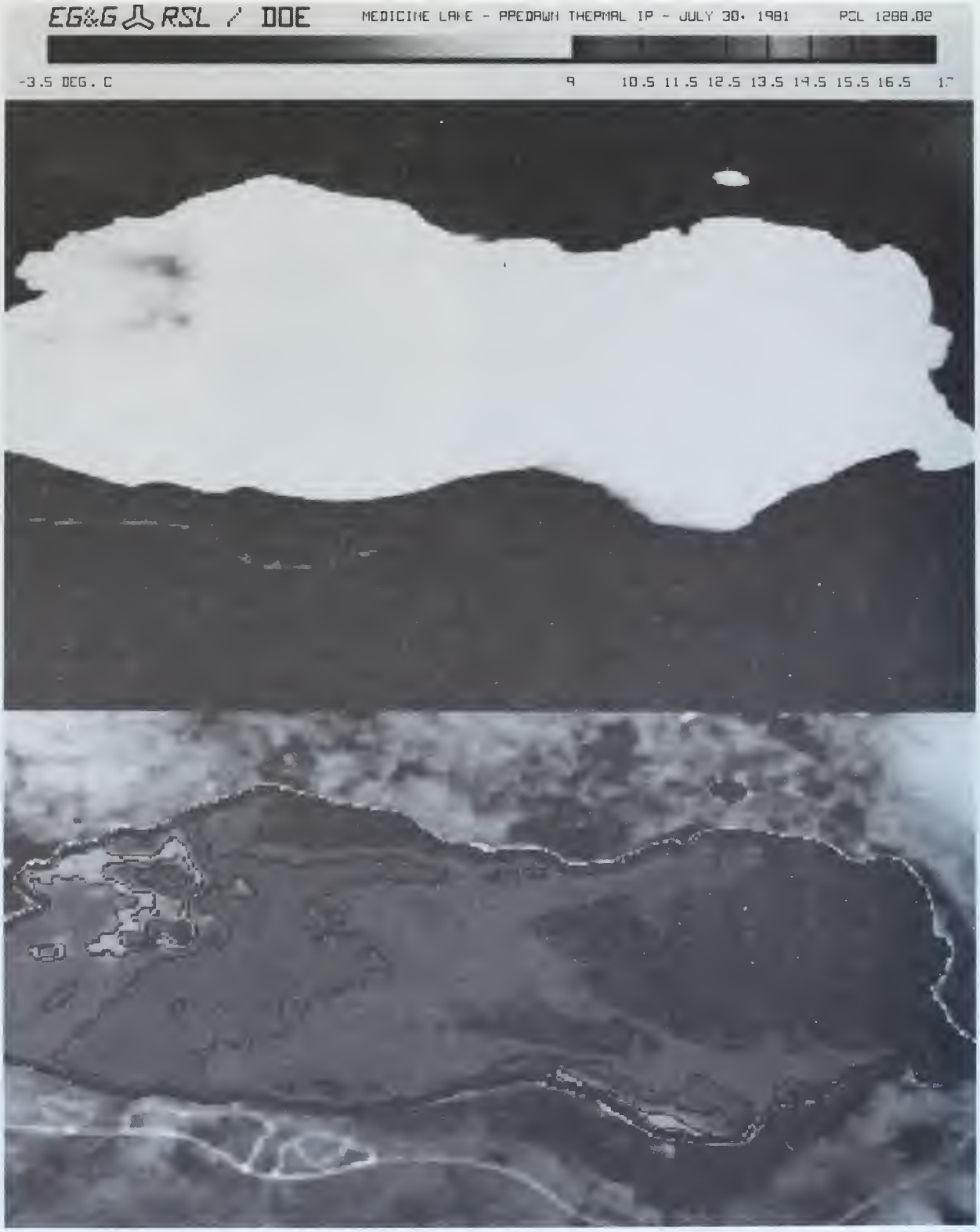

EG&G RSL / DOE
MEDICINE LAKE - PREDAWN THERMAL IR - JULY 30, 1981
PCL 1288.02
-3.5 DEG. C
9
10.5 11.5 12.5 13.5 14.5 15.5 16.5

Figure 3

thermal anomalies cannot be mapped on the aerial photographs.

Medicine Lake, 34 miles northeast of Mount Shasta, is shown in the thermal infrared image of Figure 3. The data were calibrated and processed so that apparent temperatures -3.5°C to +9.0°C are in levels of gray, and +9.1°C to +17.0°C are in color. The scale is presented in the strip across the top of the image. The upper half of the figure shows the image of the lake before processing and coloring; it is difficult at this contrast scale to discern temperature zones within the lake. The lower half of the figure has been processed and color-coded (unfortunately, reproduced here in black and white). In addition to the color-coding, the image has been enhanced by the addition of isotherms. The first interval on the temperature bar represents a 1.5°C change in temperature with subsequent intervals representing a 1.0°C change. Above 15.5°C, the intervals are halved to 0.5°C. A brief comparison between the upper and lower halves of the figure demonstrates the advantages of color-coding and contouring. While some discrimination is possible on the upper image, it is much easier to detect thermal differences on the lower image. These two images are derived from the same data; the color-coding and contouring are the only differences.

My organization does not do any interpretations or analyses. This is being done at the U.S. Geological Survey after we deliver the data. For the Cascades volcano surveys, we produced about 40 computer compatible tapes, and spent about four weeks in the field. Precise navigation of our lines was ensured by microwave ranging stations positioned on the ground. This method allows straight flight lines which could be reflown again to within a few hundred feet at a later time.

DISCUSSION

Question: I didn't note any pronounced change in temperature with elevation. Was that corrected out?

Ginsberg: No, those are the apparent temperatures as seen from the aircraft; so the lower levels, predawn, should be cooler.

Question: Are those actual surface temperatures?

Ginsberg: No, those are what are called apparent temperatures. There was no attempt to remove the effects of emissivity or altitude.

Question: Was there any adjustment going to be made for the amount of moisture in the air?

Ginsberg: There can be, but we didn't do this. This is one of the reasons for filtering at 8.5 microns, which minimizes the effects of water vapor. At only 2,000 feet above the summit, the effect is small; the tendency would be to smooth out thermal gradients, and since we are not striving for absolute measurements, we are not too interested in that. We are more interested here in gradients.

Question: According to our volcanic hazard specialists, we shouldn't be just looking at the main volcano. Did you fly some of the surrounding areas for interpretation?

Ginsberg: Yes, at U.S. Geological Survey request. We did it two ways: one was an aerial coverage of a few miles square around their chosen area, and then there were some single lines across the volcano summit that were of special interest to them.

Question: Who was your contact with the U.S. Geological Survey?

Ginsberg: One of them is here, Jules Friedman, who is our contact at Denver. Another is at Flagstaff, Hugh Kiefer.

Question: I wonder if any similar type of scans have been made of non-volcanic geologic features as a control?

Ginsberg: We have flown geothermal areas in Nevada, New Mexico, and California, and we have also flown in non-geothermal, non-volcanic areas. These sharp anomalies are

only present in the volcanoes or in geothermal areas -- you don't see them in other areas at all.

Question: That hot area on the north side of Mount St. Helens on May 16, is that from emissivity or what?

Ginsberg: No, that is not emissivity. If you look at the aerial photographs, they show no color changes matching that in the visible. So it is not a different rock type that you are seeing that might have a different emissivity. At any rate, that bit of difference in apparent temperature would be difficult to explain on the basis of emissivity differences in rocks.

Comment from the floor: In relation to that question, the areas that showed thermal anomalies in the imagery on the north side of Mount St. Helens were the same areas where the ground was steaming; so it could have been related to the real thermal anomalies.

Ginsberg: Yes, where you see a red spot with a yellow and purple halo is usually the steam coming out, but there are areas around those that can't be seen visually.

Question: Were there any of those warm areas covered with snow?

Ginsberg: No.

Question: Would this technique be possible from satelites?

Ginsberg: It is possible from satelites, but the resolution is probably no better than one km by one km on the infrared satelites. This airborn imagery has five foot pixels instead of one km.

Comment: I guess the answer is no.

Ginsberg: Not with that resolution, no.

McBirney: I may be missing something here, but you are very proud of the fact that you have taken pictures that show us that a place that is steaming on the ground is hot. My question is, what do we gain in return for this $20,000 that we don't see on the ground?

Ginsberg: The purpose was not to find the steaming areas since those are visible. What you can get is apparent temperature differences of the order of a tenth of a degree Celsius or larger, over large areas, and from these we can produce thermal maps and do thermal flux calculations or measurements over the area. You can also go back periodically to thermal areas and note changes. I think that is the advantage. Also, some areas are quite rugged and though they are not steaming, are pretty hot and you can still see them.

PANEL DISCUSSION I

FORECASTING ERUPTIVE ACTIVITY IN CALIFORNIA - APPROPRIATE MONITORING METHODS FOR THE DIVERSE VOLCANIC ENVIRONMENTS

MODERATORS: Robert Decker
Alexander R. McBirney

PANEL: Roy A. Bailey
Robert L. Christiansen
Clive F. (Rick) Kienle
Stephen D. Malone
William G. Melson
Donal R. Mullineaux
Donald W. Peterson
Clement F. Shearer

Robert Decker: To start out, let me pose a question that has been touched on by several speakers, in the hope that we may have, or may be able to develop, a consensus of topics. What portions of the state have the greatest probability of volcanic eruption? What information is required to establish priorities for the study of these potentially active volcanic areas?

Roy Bailey: As I stated earlier, I feel that probably the Mono Craters, including the Inyo Craters, are the system of volcanoes in the United States that are almost as active as Mount St. Helens has been. Based on what I have seen of the data gathered so far, it is probably the area most potentially capable of erupting.

Alexander McBirney: What would you do about it?

Roy Bailey: The first action would be to initiate ground deformation studies in the area. Ground deformation, based on observations in Hawaii, Mount St. Helens, and probably in Long Valley, gives information prior to seismic activity. In Long Valley, the bulge developed between 1975 and 1980; the earthquakes occurred in 1980. Horizontal distance measurement data, however, suggest that the bulge occurred over a span of at least a couple of years, possibly during the time that the foreshocks were taking place in the southern part of the caldera. Plans are to have some type of deformation monitoring network in Long Valley and hopefully in Mono as well, by next summer.

Bob Christiansen: Following from Roy's description of the bulge at Long Valley, and from Bob Decker's diagram of uplift at Pozzuoli, there are other locations where we have seen large areas of deformation that do not necessarily form a bullseye at which the point of eruption will occur. Another example is Japan's Sakurajima volcano, which is on the south side of a large caldera -- although the deformation is not as large as that at Long Valley caldera. When Sakurajima erupts, deflation is not immediately beneath it, but rather distributed over an area (Kogoshima Bay) to the north, which apparently is a large submerged caldera.

So one of the things that we must bear in mind is that, in this kind of analysis, where we may see a pattern of deformation, it will be of great interest and significance in trying to analyze its volcanic potential, by itself, but the pattern may not necessarily locate the point of outbreak of any ensuing eruption.

Rick Kienle: In light of the Steve Malone and Bill Melson argument about the causative mechanisms of the Mount St. Helens major eruption (did the earthquake trigger the eruption or did the extreme magma pressure trigger the earthquake?), this question, as it pertains to prediction capabilities, has even greater significance at Long Valley. Acknowledging our poor ability to predict tectonic earthquakes, I don't feel very confident that seismic monitoring could forewarn us of a major eruption in a tectonically active area such as Long Valley, if one of the earthquakes caused enough change in the stress field to unroof the magma chamber.

Don Mullineaux: I would like to return to the subject of probability of eruption and add the factor of how many people and how much property are at risk. Based on the geologic record, Mono is immensely impressive in its history of explosive, dangerous volcanic activity and, also in its being a very heavily used area. Lassen Peak is also an area of high probability, although not as high as Mono. This view is not unanimous. Rocky Crandell feels that Lassen is more likely to erupt first. Lassen is also an area where there are fewer people at risk and control around the volcano is easier because it is National Park land. Mount Shasta also has a high probability, perhaps not as high as Mono, but because of the communities that are directly on the flank of the volcano, the severity and consequences would be very high. If Shasta were to erupt, it would pose the same kind of very severe problems that Mono would. What do you do if you have the apparent threat of an eruption? It has been pointed out that these things may go through all of the preliminary motions and do nothing, or they may go through the same preliminary motions and continue into a very dangerous eruption.

Question: If there were a major eruption at Mono Lake, is that likely to affect the Los Angeles Light and Power [facilities], and if so, how much?

Roy Bailey: At the least, Los Angeles might have to look for a new source of water.

Question: How cheaply can the monitoring systems be emplaced? Because eruptions are so infrequent, it is very difficult to convince the layman that they are necessary.

Steve Malone: A seismic station, including some manpower and the miscellaneous odds and ends that go with it, costs about $5,000 each. But that does not include the recording end or the people that are going to interpret the data. This figure can vary greatly. I think that in California, for the first stage of monitoring, there probably are enough existing stations around to detect most types of events very early. I am not sure about Modoc County. The area east of Mount Stasta might need additional seismic stations. There must also be the capability to react rapidly if something does occur, not only with seismic equipment, but geodetic equipment as well.

In regard to Roy Bailey's belief that slow earth movements precede the seismic activity, at Mount St. Helens this does not appear to be the case, at least back in March. There does not appear to be any evidence that there were measurable geodetic changes beforehand. However, there wasn't much sensitive geodetic equipment in there ahead of time, so we don't really know for sure.

Bill Melson: There are some less expensive geodetic techniques, such as "dry tilt" that we [Americans] have developed and actually exported to other places, where it is used very well. "Dry tilt" simply requires a surveyor, an assistant, three or four bench marks, and a level. This method is very reliable. It's still used in Hawaii, and scientific people and their staff can do it on their own. It does have some shortcomings, but nonetheless it does tell you what the plane you're on is doing and at a very sensitive level. It's accuracy is $\pm$ 2 to 3 microradians, which is 2 to 3 millimeters per kilometer, and it can be installed in any area where you suspect there is deformation. The level instrument cost is about $1,500.

Bob Decker: Let me tell how "dry tilt" got its name. On Hawaii, tilt measurements,

with a water tube tiltmeter, got to be called "wet tilt" because the procedure used to clear air bubbles from the water tube lines left a large amount of water on the ground around the pots. You then had to lie down on your stomach to look at the micrometer screw and, of course, you were lying in the water. This became known as "wet tilt." When it was found that you could make tilt measurements without lying in water, it was automatically called "dry tilt."

Don Peterson: I detect a certain amount of competition growing between those favoring seismic monitoring methods and those favoring geodetic methods. I think this is unfortunate because both methods, including "dry tilt" instrumentation, are vital and should be used together. This team of instruments would be very important and useful if established at each of those potentially active volcanic areas in California. The Geological Survey, last summer, established both geodetic and "dry tilt" networks on both Shasta and Lassen with plans to extend them to other Cascade volcanoes. The Long Valley and Mono areas were not included under this program, however. I feel they should be.

Steve Malone stated that there was no evidence of ground deformation at Mount St. Helens prior to March. One possible reason was the lack of an extensive deformation network. There was only one line established several years previously on the east side of the mountain. It was re-occupied after the eruption and showed no change. One geodetic line is obviously not sufficient. Had a network, similar to that now in operation on Shasta and Lassen and Baker, been in existence at Mount St. Helens, it might have provided some useful information. The geodetic network at Mauna Loa began to show changes during the summer of 1974, several months before any increase in seismicity.

The seismic and geodetic methods should be operated together because they supplement each other. Both the electronic distance measurement and dry tilt methods are effective and are relatively inexpensive to install in relation to the possible consequences.

Bob Decker: Clem Shearer, is the risk to society worth all this monitoring?

Clem Shearer: A strong impression that I have received of the proceedings so far is the uncertainty of scientists either regarding monitoring methods or hazards assessments in general. A serious responsibility that we have is to provide usable information to public officials. The type of information that they want is what we cannot really give them: information such as, exactly when will an eruption occur and what will it be like. Despite all of the uncertainties, I think that our hazard assessments are valid enough to be used to take preventive action. These assessments may not help us to clearly understand all of the volcanic processes, as Dr. McBirney pointed out, but I think that we understand the consequences well enough that we can prepare for them. Despite the uncertainties, hazards assessments are well worth the investment.

Bob Decker: Up until the eruption of Mount St. Helens in 1980, all of the money contributed by federal and state governments, academic instutions, and the National Science Foundation that went into studying active volcanism totals about five million dollars per year as a national effort. This would be up to maybe $20 million per year subsequent to the eruption of Mount St. Helens. A $20 million per year program is a ten cent per year investment to each person.

Comment (Bates McKee): We should take advantage of what is almost free academic help, especially in monitoring areas like Mono Craters. If each potentially active area were assigned to a particular institution, such as the University of Nevada, and you told them what you wanted, set up benchmarks, etc., the monitoring could be done at a fraction of the cost of flying government scientists around.

Question (Neil Suneson): Did Weyerhaeuser contribute at all to the effort to study Mount St. Helens? Is there any way federal

or state governments can obtain contributions from private industry when the industry stands to lose equipment or lives in a disaster such as Mount St. Helens?

Rick Kienle: They did use private consultants and they spent a lot of time communicating with the scientists in Vancouver to find out what they could do to protect themselves. There wasn't much that they could do to protect their property, but they certainly made every effort to protect their people, consistent with the level of alertness that existed before May 18. Since May 18, they have been very cautious.

Don Mullineaux: Before May 18, Weyerhaeuser did have a lot of people in the field, and a lot of people knowledgeable of local geography and conditions. They were a good source of observations. There did not appear to be any problem with the interchange of information between the var- ious federal, state, and county agencies in Vancouver, and the private companies who were working on or around the volcano. I thought the exchange of information was very good.

Rick Kienle: Getting back to the original question, I don't think Weyerhaeuser directly funded any research on the volcano before May 18. As far as I know, the only people in the industrial sector that had funded basic research on the volcano were the owners of nuclear power plants and the owners of dams right on the volcano.

Don Petersen: In further answer to Neil Suneson's question, Pacific Power and Light, which operates the system of dams and reservoirs on the Lewis River, south of the volcano, became concerned about what was going to happen during the next winter. The concern was for the continual monitoring that was going on around the mountain and the kind of weather that is characteristic there. As a result, Pacific Power and Light designed and financed a system of steel towers. Using our advice on where to locate them, they deployed these towers on the mountain so that geodetic studies could be continued through the winter. Their experience with power lines proved invaluable in the assembly and installation of these towers.

Rick Kienle: The Weyerhaeuser people have contributed considerably since May 18. Once they observed what the potential for damage was, they became quite concerned about protecting themselves in the future. They have not only collaborated with the Water Resources Branch of the U.S. Geological Survey, but have also supported basic research on what the volcano is apt to do next. The Portland General Electric Company has supported hydrologic research on changes in the Toutle and Cowlitz rivers. The research on potential flooding in these rivers, and the damage done by the eruption, have resulted in the modification of evacuation routes around the Trojan nuclear plant.

Bob Decker: Let us shift the discussion somewhat. What types of earth science research are needed to improve our capability of dealing with volcanic eruptions in California? Perhaps we should get back to the more basic research, not just monitoring techniques but perhaps even back to plate tectonics. Our observations are probably running ahead of our interpretations, and our speculations are not precise enough to set up models that we can test with observational and experimental data.

Alexander McBirney: I have given a lot of thought to that question and feel it ties in with a previous question: Why don't we draw the universities into these programs?

When Mount St. Helens went off, my colleagues and I went through agonies trying to decide what to do. The final question was to do nothing, that is, in terms of actual field work. The reasoning was, first of all, the magnitude of the effort required was overwhelming. Large numbers of people had to be obtained and set up. This was beyond our capability -- and this is especially true when you're giving ten lectures a week at a university. You are not the person to be on top up there during this kind of an

emergency. The same is true of graduate students. Although, in a sense, they are a source of cheap labor, you still have to train them. And is this the appropriate place for training under these emergency conditions? I think the role that the university should play is in the field studies -- assigning a student to a particular volcano and telling him to find out what has been going on there.

Of the various research topics to be considered, I am most interested in those techniques in which we could detect the rise or migration of magma. But there are other factors related to the actual mechanism of the eruptive process. We know that volcanoes have a wide range of eruptive behavior, and this is related to magma viscosity, gas content, the time of repose, and so on, but there are other complex factors involved such as ground water interaction and the physical strength of the surrounding rocks. I would feel skeptical of any program that set out saying they were going to solve the problem of volcanic eruptions and assign various individuals to work on different aspects of it. That rarely works. People normally do what they want to, take your money, and interpret the work that they were doing before as contributing to that project. In the end, I think, nevertheless, that this type of investigation usually pays off.

Bill Melson: In regard to how universities could be more active in these types of studies, I think we find ourselves inadequately trained to do volcanology. The "dry tilt" methods are specialized and proven to work. However, as a geologist or geophysicist, you won't find this method in your plane table course at school. You won't find many of these specialized techniques that we're using in the university curriculum. Studies should be modified, especially in the area of precision surveying, to include electronic data measurement techniques. The geology curricula needs sharpening up in geophysics so that projects such as these projects can be taken on easily by students and faculty advisors.

Alexander McBirney: I would certainly agree with that.

I would like to hear more from Dr. Kienle regarding interaction between the scientist, industry, and the public. Could you suggest some ways in which this interaction could be improved to provide more pertinent information to those who need it?

Rick Kienle: Right now is the time to approach private industry that may be potentially affected by volcanic activity, and it may be in their best interest to spend some money to protect themselves. I don't think that it is necessarily incumbent upon the U.S. Geological Survey to do that because they are already collecting a large amount of money from these industries through the federal government, but I certainly think that these industries can lobby for more support for the Geological Survey. Weyerhaeuser has done this in favor of going to their Congressmen to get money for everything they want. Certainly they have gone and lobbied for continued money for the Corps of Engineers' efforts to keep the Toutle River cleared out and this sort of thing. It is certain that industry can be, if nothing else, an active lobbyist. This is something we feel is important, and I do too. In the case of Weyerhaeuser, it has been really effective -- not as effective, however, as we would like. I think that people from universities probably have a better chance. I know that those at Portland State University do a fair amount of consulting for Weyerhaeuser. They don't do it specifically in reference to volcanic hazards; they do it more particularly with federal reference to their mineral resources program. Portland State University has a good working relationship with Weyerhaeuser; so when the problem came along, Portland State was the first place Weyerhauser looked for volcanic expertise. They went to Paul Hammond. Then the Survey entered the picture, and there was a nice, cooperative effort that evolved there eventually. I think that is still very successful.

In terms of a direct funding, it is a matter of university people going to industry with a program that can be shown to be cost-effective -- basically, one that will provide the industry with insurance. In many cases, particularly with timber companies, this can

be something that is not particularly expensive. It's simply, "Don't build the mill down in the bottom of the valley or on the flanks of Mount Shasta." But this kind of thing is not done. It certainly has not traditionally been done on the west coast. As far as I know, the few places that there have been any kind of volcanic hazard zoning have been in places where people like Don Mullineaux and Rocky Crandell have done detailed studies to show the need for it. With the present-day awareness of volcanic hazards, now is the time for people to go to private industry and say, "Look, I want to show you a volcanic hazards study, and it is only going to cost you $10,000 for your property." I haven't had to go out particularly and recruit clients on this because we have been pretty busy with ones we have had, but I can see this coming. I see other people doing it, and I think it is a good thing -- not just for private consultants like myself but for the U.S. Geological Survey. They can go to state or county governments, and universities can go to municipalities, etc. I think that there is a wide range of funding opportunities that are possible that will hopefully decrease the hazards of volcanoes. I don't think that you need to get worried about doing fancy monitoring things or esoteric studies at this point in time with industry financing. I don't think that they have the level of comprehension of what you as geologists are doing to see the cost effectiveness in it. Clem, do you have a response to that?

Clem Shearer: Well, my audience is a little bit different. It isn't really industry as much as it is the public officials. But consider other hazards such as earthquakes. Certainly industry has known for a long time that they have been severely affected by earthquakes, yet they have not really come forth with money for research.

Rick Kienle: I disagree with that. I think that...

Clem Shearer: Well, basic research. Research into how they can protect themselves. Yes, a lot of them have, Bell Industry, computer firms, and so forth, are very interested in it -- in how it can affect their equipment. That sort of thing they'll work on, but so far, as basic earth science information, they haven't contributed much. I would do the same thing if I were a businessman; I wouldn't spend my money there. The same thing with public officials -- they have a lot of things they have to spend money on besides volcanoes, but basically, I would agree that now is the time, because of the eruption at Mount St. Helens, to grab the attention of public officials. That is the case in other hazards; the best time to grab their attention is after a disaster and hold on to it as long as you can. One can find that in earthquakes. When have we moved forward with legislation and funding in earthquakes? Basically, after something has happened. Long Beach was an example of one. San Fernando was an example of another. You have to be an opportunist, I guess. Now I think the opportunity is right.

The relationship between scientists and public officials is a very curious one. It is not an easy one to fathom. It is very easy for one group to blame the other group for the problem of lack of coordination in communications, but the gap is not impossible to bridge. I think largely it involves at least some of each party trying to understand the other a bit more than they have. A recent example of this, I guess, was a workshop on volcanic hazards at Mount Shasta, which was held about three weeks ago in the town of Mount Shasta for local response officials and planning officials, and the workers from the state also. That was a joint effort of the Geological Survey -- we did put up a lot of the money -- and a lot of the planning was done by the State, both the Division of Mines and Geology and the Office of Emergency Services. The Mount Shasta workshop had a different kind of forum than this, largely because the audience was different and the needs were different. One thing you have to realize is that the public officials all have different information needs. They all need information presented to them in some format or another. Formats such as this, a workshop format, where actually meeting and talking face-to-face is useful largely because there are these great uncertainties. They do not particularly know what to do with these uncertainties, to

a large degree. A county official in San Bernardino suggested that the first official earthquake prediction transmittal would be so vague and so awash with uncertainties as to be completely useless to them. That is essentially the kind of feeling they have. I think it is unnecessary. I think about the only way that we are going to bridge that is to more or less train them, as you suggest, and train the scientists in exactly what they can do with these uncertainties. They worked with uncertainties at Mount St. Helens fairly well, and I think they can work with the uncertainties at Mount Shasta pretty well, and at Long Valley fairly well.

Rick Kienle: I think that is a traditional problem that we have as scientists, working not just with industry but with the public officials and the general public at large. We tend to speak as a scientist in very concise terms. That implies that you know the exact answer to the question that is being asked, and the public perceives the scientist as either having the answer to the question asked, or "to hell with you!" I think this is something that, in a sense, we have brought on ourselves. Scientists are viewed as part of the elite in society, and as such, we are supposed to provide good answers for our pay, which we all hear a lot of complaining about. But, as was said earlier, we do what we want to do, and we are fortunate if somebody pays us to do it. That is an attitude most of the public can't get away with, and I think there is some resentment there, too.

PART II

HUMAN RESPONSE TO VOLCANIC DISASTERS

HAZARDS PLANNING AND EMERGENCY OPERATIONS

SPECIAL HUMAN BEHAVIORAL RESPONSE ASSOCIATED WITH VOLCANIC HAZARD CONDITIONS

Dr. Gilbert F. White, Director
Natural Hazards Research and Applications Information Center
University of Colorado, Boulder, Colorado

INTRODUCTION

Because the experience during recent decades with volcanic eruptions in industrial societies is relatively sparse, it is helpful to begin with a few generalizations from other hazards having applicability to possible volcanic events in the western United States. These include response to warnings, evacuation measures, and cultivation of awareness to mitigation measures. The activities preceding and following the Mount St. Helens eruption offer grounds for a few more specific observations on what measures are likely to be helpful in what circumstances.

About ten years ago, I was one of a small group of specialists appraising where the United States stood with regard to understanding the risks of natural hazards and mobilization of the scientific community in dealing with them. We reviewed experiences with floods, earthquakes, hurricanes, and tornados; but volcanic eruptions were considered somewhat arcane at that time. We were aware that there were some volcanology professors, and some geologists in Denver, who felt that volcanoes presented a hazard in the United States, but, in general, volcanic activity was considered phenomenological.

RECENT DEVELOPMENTS

This workshop couldn't have been put on ten years ago with the kind of participation, interest, and the character of scientific discourse we have today. Much credit is due to James Davis, Jan Denton, and Alex Cunningham for their foresight, sense of responsibility, and initiative in organizing this meeting. They recognized that two significant developments had occurred to make this event appropriate and timely. The first is the Mount St. Helens eruption, an event which brought credibility to the subject of volcanic hazards in the United States. The second is the development of a deeper understanding of the phenomena involved, physically, in terms of scientific understanding and risk assessment, and socially, in terms of mitigation and crisis management methodology.

In recent years, largely as a result of our changing sensitivity to environmental problems and the increased public interest in "extreme events," much information has been gathered to enable us to deal with or predict volcanic disasters. The well-known geological studies by Crandell and Mullineaux and their colleagues in the U.S. Geological Survey have established confidence in the field of volcanic risk assessment. Continuing geophysical studies in Hawaii, Japan, and other parts of the world have demonstrated a deepening understanding of volcanic processes and near-term prediction techniques. The subject of plate tectonics has developed as a worldwide framework for continued development of theoretical volcanologic studies.

CONTRIBUTIONS OF SOCIAL SCIENTISTS

Studies of the social aspects or implications of such predictions have also progressed significantly over the last ten years.

These studies have underlined the importance of acquiring a basic understanding of both the physical and social systems in order to plan and take the actions necessary to ensure the safety of large sections of our population. Today, the risk of an extreme event can be quantified, at least on a regional basis. But it has become clear from various studies that some kinds of warning messages are more effective than others in obtaining the desired response from the public in the affected area. Specificity is of prime importance in determining how the public will accept and respond to the message. Credibility of the person or agency issuing the warning is equally important. We can now say with considerable confidence that knowledge about a forthcoming event, as determined by the physical scientist, can either be highly effective in stirring appropriate constructive action by the people affected or can be useless, depending upon the character of the message, the way it is stated, the channel through which it is communicated, and the number of times and circumstances in which it is given. The manner in which scientific information from the geologists and geophysicist is treated and delivered to the public will determine the degree of cooperation of the public. There is always a Harry Truman resisting efforts of evacuation from a hazard zone. Without proper regard to establishing credibility by local officials, and development of effective communications based upon specific information, we could have a large population of Harry Trumans.

While mitigation is gaining increasing acceptance as the appropriate course of action, several important problems have been recognized as barriers to our effectiveness. Among these:

1. A person's awareness or perception of a particular hazard often has no direct relationship with the information he or she is given about the hazard.

2. There is no necessary relationship between the individual's awareness of the hazard and his or her personal actions.

3. There is no clear causal link between what people say and what they will actually do.

There are circumstances in which people will become more aware of certain risks than otherwise, and there are circumstances that will influence the extent to which they will take appropriate action. Certainly, we have found simply writing a report on a hazard and distributing it does not ensure that the information will be used at the local level. These findings underscore the importance of an informed, intelligent approach to disaster mitigation.

ADVICE TO SCIENTISTS AND PLANNERS

As we digest the wealth of information presented by representatives of various disciplines concerned with volcanic hazards risk assessment, eruption prediction, hazards mitigation, and crisis management, I have the following comments to ask you to consider regarding (1) prediction, (2) precision in communication, and (3) the treatment of a low-frequency, high-consequences natural hazard.

Scientists should consider the limitations to their ability to make specific predictions of volcanic activity. It appears we have come a long way in delineating the areas of California subject to volcanic risk. One is tempted, however, to compare the confidence of some scientists, fresh from their Hawaiian and Mount St. Helens' studies, with the earthquake prediction researchers of a decade ago.

About ten years ago, in some scientific circles, there existed an interesting combination of euphoria and skepticism about earthquake prediction. Some felt that the capacity to make a relatively accurate prediction about the size, location, and time of occurrence of a major seismic event was almost within reach. These feelings were expressed so enthusiastically that social scientists joined the fray by studying the social implications of making such predictions.

The euphoria has not, however, been fully realized. Although there have been a few successes, there have also been notable failures. As a result of the difficulties in predicting the specifics of where, when, and how large an earthquake will be, we have

scaled down our emphasis on prediction techniques to concentrate more on regional assessments, stressing location of future earthquakes.

We need to recognize this in our volcanic hazards research. As we gain more information and experience with volcanic systems, our efforts at predicting the specifics of the volcanic events is likely to become more difficult. We should ask ourselves whether we are now better able to predict volcanic eruptions than we were able to predict earthquakes. All will undoubtedly realize that we seem close enough to our goal in some situations to encourage further research into prediction techniques. But all of us -- scientists, administrators, and public alike -- must determine how much faith we have in our ability to predict volcanic eruptions.

STATESMANSHIP IN VOLCANIC PREDICTION

Under public and media pressures, researchers attempting to predict volcanic events may face a psychological problem. This problem, which I call the "Guadalupe-Palmdale Complex," is derived from predictions for which the events did not materialize. Scientific groups or agencies, in essence, have been embarrassed because they have alerted the public, sometimes causing great anxiety, without enhancing their own credibility. Such caution has, to some extent, been challenged by individual scientists who, responding to the media's desire for a good, precise prediction of a horrible event, bend or bias their data just a little bit to lend support for their concern. It is extremely difficult for the individual scientist, faced not once but repeatedly with pressure to express an opinion about a possible event which he or she knows may be a matter of great consequence in the future, to refrain from doing so. We all have to learn how to deal with being able to correctly predict five out of ten eruptions, while predicting another five out of ten that failed to materialize, and still face the possibility that other quite unexpected events may materialize in the same time-period. This is the kind of situation that calls for scientific statesmanship on the part of those who generate and interpret the basic information.

THE IMPORTANCE OF COMMUNICATION

It is important that we cultivate precision and understanding in the interpretation of scientific information. Good examples of this were demonstrated at Mount St. Helens, where the USGS and FEMA required collaboration with several fields of science. We need to consider the terminology we use, not just in a prissy concern for phraseology, but in terms of what it connotes to the people using it. For example, what is an "active volcano" in terms of days, months, or years? At what time is an "inactive volcano" redesignated as an "active volcano"? We should attempt to cultivate some concensus of meaning for the terminology used. If you doubt the importance of cultivating such understanding, consider the experience of the nuclear industry in the last ten years. The nuclear engineers knew what they thought the risks and consequences were and assumed it would be easy enough to communicate the same connotations to the common person. If there has been any great surprise in the past decade, it has been the surprise experienced by the proponents of nuclear power and nuclear waste disposal at the way in which many publics in the the United States and the western world have failed to understand their interpretations and connotations of safety and risk. We are dealing here with a similar kind of problem. The more we talk about the risk attached to volcanic systems and their activity, the more important it is that we be precise in these several connotations.

APPLICATION -- THE TIME IS NOW

Because volcanic disasters are low-frequency phenomena which have high consequences, we need to think carefully about how we communicate this information to organizations whose primary functions are other than concern about volcanic phenomena. If another Mount St. Helens-type event does not occur in the next few years, the level of interest sustained by many publics will decrease, and our concerns for

public safety may then seem quaint to many local officials concerned with disaster mitigation. It is important for us now to think about ways in which this concern can be incorporated in a practical way into the daily operations of organizations which exist for other purposes: local planning agencies, emergency preparedness organizations, and private industry. Volcanologists must not allow themselves to become (again) an obscure fraternity of esoteric specialists. They need to find ways to effectively relay their information and concern to the groups that will be able to use it appropriately.

We do not have to delay the application of knowledge already available while steps are taken to improve our ability to forecast another volcanic eruption. The principal volcanic hazard areas in California are already sufficiently well-defined to initiate actions that will be effective in mitigating the hazard when an eruption occurs, and, meanwhile, to preclude unwise construction or encroachment into clearly hazardous areas. This sort of immediate application needs to be pushed along with our efforts to understand other aspects of volcanic hazards. Continued effort in clarifying and maintaining communication within the scientific community and with public administrators is essential for proper application of the impressive volcanologic knowledge which has been gained during recent years of research and experience.

REFERENCES

Anonymous, 1980, Volcano cabin owners to defy "stay out" order: Seattle Post Intelligencer, May 17, 1980, p. A5.

Crandell, D.R., and Mullineaux, D.R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 25 p.

Green, Marjorie, Perry, and Lindell, 1981, The March 1980 eruptions of Mount St. Helens; Citizen perceptions of volcano hazard: Disasters 5, n. 1.

Harnly, Caroline D., and Tyckoson, David A., 1981, Mount St. Helens, the 1980 eruptions; A bibliography: Vance Bibliographies, Monticello, Illinois, n. P-786.

Hirose, Hirotada, 1979, Volcanic eruption and local politics in Japan; A case study: Mass Emergencies, v. 4, p. 53-62.

Kartez, Jack, 1982, Emergency planning implications of local governments' adaptive response to Mount St. Helens, in this volume.

Kilijanek, Thomas S., 1981, There she blows: The search and rescue response to the Mount St. Helens volcano: University of Denver, SAR Research Project Technical Report 11.

Leik, Robert K., and others, 1982, Under the threat of Mount St. Helens; A study of chronic family stress: University of Minnesota, Family Study Center.

Perry, Green, and Lindell, 1980, Human response to volcanic eruptions; Mount St. Helens, May 18, 1980: Battelle Human Affairs Rescue Centers, 400/80/032.

Perry, R.W., 1979, Incentives for evacuation in natural disasters; rescue based emergency planning: Journal of American Planning Associations, v. 45, p. 440-447.

Saarinen, Thomas, 1979, The relation of hazard awareness to adoption of approved mitigation measures: Hazard Awareness Workshop, March 22-23, 1979, Corpus Cristi, Texas.

Saarinen, Thomas, 1980, Public response to Mount St. Helens volcano hazard warnings: National Science Foundation, Problem-Focused Research, Washington, D. C.

Sheets, Payson D., 1980, Archeological studies of disasters; Their range and value: University of Colorado, Institute of Behavioral Science, Working Paper no. 38.

Sheets, Payson D., and Donald Grayson, editors, 1979, Volcanic activity and human Ecology: New York, Academic Press.

Simkin, Tom, and others, 1981, Volcanoes of the world; A regional directory, gazetteer, and chronology of volcanism during the last 1
Press, New York.

Sorensen, J.H., and Enckseat & Mileti, 1975, Landslide hazard in the United States; A research account: NSF-RA-E-75-016.

Sorensen, John H., 1981, Emergency response to Mount St. Helens' eruption; March 20 to April 10, 1980: University of Colorado, Institute of Behavioral Science, Working Paper no. 43.

Sorensen, John H., 1982, Emergency planning for rare events; Some behavioral science lessons for volcano hazard management, in this volume.

U.S. Forest Service, 1981, Mount St. Helens land management plan: Final Environmental Impact Statement.

U.S. Federal Emergency Management Agency, 1981, Mount St. Helens Scientific Workshop, November 13-14, 1980: Proceedings.

U.S. House of Representatives, Committee of Ways and Means, 1980, The economic effects of the eruptions of Mount St. Helens.

U.S. Geological Survey, 1980, Hydrologic effects of the eruptions of Mount St. Helens, Washington, 1980: C r r 850.

Warrick, Richard, 1975, Volcano hazard in the United States: University of Colorado, Institute of Behavioral Science, NSF-RA-E-75-012

Warrick, Richard, 1979, Volcanoes as hazards, in Sheets, P., and Grayson, D., editors, Volcanic activity and human ecology, Academic Press, New York.

Warrick, Richard, 1981, Four communities under ash after Mount St. Helens: University of Colorado, Institute of Behavioral Science, Monograph 34.

Washington Department of Social and Health Services, 1981, Project ashlift: A Mount St. Helens disaster assistance and crisis counseling program: Report of the Mental Health Division.

Washington State University, 1980, Proceedings of Washington State University's Conference on the Aftermath of Mount St. Helens, July 8-9, 1980, College of Agriculture.

EMERGENCY PLANNING FOR RARE EVENTS: SOME BEHAVIORAL SCIENCE LESSONS FOR VOLCANO HAZARD MANAGEMENT

John H. Sorensen
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

SUMMARY

The purpose of the research which forms the basis of this paper was to describe and analyze the response of public officials to the initial eruption of Mount St. Helens volcano in southwest Washington. The period covered was from March 20, 1980, when the first seismic activity was noted, to April 10, 1980, when the Emergency Coordination Center (ECC) was activated. Specifically, the research sought information on:

1. The structure of emergency response organizations and efforts;
2. Information flow among emergency response officials;
3. Dissemination of information to the public;
4. Problems and issues associated with emergency response activities;
5. Public attitudes towards those issues; and
6. The processes and means by which emergency decisions were made.

Data were collected during the week of April 6, 1980. Information observation of ECC activities and meetings were made. Second, structured interviews with representatives of emergency response organizations were conducted. Third, editors of local newspapers were interviewed and papers were collected for analysis. Finally, 120 people in the vicinity of Cougar, Washington were interviewed about their perceptions and attitudes toward the eruption and related issues.

Initial analysis of the data lead to the following conclusions and observations:

1. The Forest Service's strong response to the impending eruption facilitated a coordinated response and reduced confusion.
2. Most local and state agencies and organizations were poorly prepared to respond to the eruption despite U.S. Geological Survey hazard studies which suggested an eruption was likely.
3. The State of Washington Department of Emergency Services did not play a major role in this initial response effort.
4. Since the volcano threatened a number of political divisions, coordinated response was hampered by jurisdictional problems and conflicts.
5. As the situation developed, more organizations attempted to become involved and competition for authority became more pronounced.
6. Much of the communication was uni-directional.
7. Many public officials felt that they were not getting enough interpretative analyses of what was taking place with respect to the eruption.

8. Local efforts to respond were hampered by the lack of definitive and understandable risk information.

9. Rumor was not a major problem.

10. Response officials had weakly defined images of the nature of a catastrophic eruption and its consequences.

11. Decisions over emergency response issues were made in a mode that resembles a rough form of benefit risk analysis. Risks were frequently traded off against the costs of an action.

12. Major issues at the time included public and commercial access, roadblock placement, financing of response activities, dam and reservoir safety, government responsibility and liability, media coverage, and information flow and warning. Space does not permit a more detailed discussion of these issues here.

This research effort and these findings laid the framework for the topics raised in this paper. Discussed, in turn, are four phases of volcanic hazard planning: risk studies, adjustment policy, hazard management, and emergency response. Using illustrative examples from the Mount St. Helens experience, recommendations for improving our ability to cope with volcanic risks are offered.

INTRODUCTION

The genesis of this research dates back to 1978, as a quick-response project at the University of Colorado, supported by the National Science Foundation. At that time I was an assistant professor at the University of Hawaii, expecting to perform the work at Kilauea Volcano, which normally erupts about every two years. Unexpectedly, I was fooled -- Mount St. Helens erupted first, and my research project was transferred to Washington. The following paper generalizes the findings from my study into a broader set of considerations for volcano hazard managment.

PLANNING FOR RARE EVENTS

Volcanoes in the continental United States erupt very infrequently, but the consequences of an eruption can be extremely high. This situation poses a classical paradox: How does society effectively prepare for and manage potential damages from low-probability, high-consequence events? The purpose of this paper is not to debate the philosophical dimensions but to outline a positive course of action for a reasonable solution to this dilemma.

Paralleling the tendencies of people to overestimate the likelihood of common events and underestimate that of rare ones, planners tend to ignore preparing for many low-probability hazardous events (Fischoff and others, forthcoming). An extensive literature documents how people from diverse locations and differing social roles deny a cause for, or use some other cognitive means to eliminate, concern over rare but threatening events (Kates, 1962; Burton and Kates, 1964; Slovic and others, 1974; Burton and others, 1978). Given this tendency, it is not surprising that it is difficult to develop a concern over or gain a constituency to promote emergency planning, particularly for events as rare as volcanic eruption in the Pacific Northwest.

Despite this disposition (which is not irrational but rather reflects concern for more pressing agenda), it is possible to prepare for such disasters without large investments in equipment or staffs. Toward that end, this paper outlines a framework for thinking about emergency planning for rare events, reviews some lessons that have been learned from emergency response to recent volcanic eruptions, as well as other rare catastrophes, and raises questions germane to developing a volcano hazard planning capability.

A FRAMEWORK FOR VOLCANO HAZARD MANAGEMENT

Effective management of volcano hazards, as well as those of other rare geophysical events, requires a comprehensive

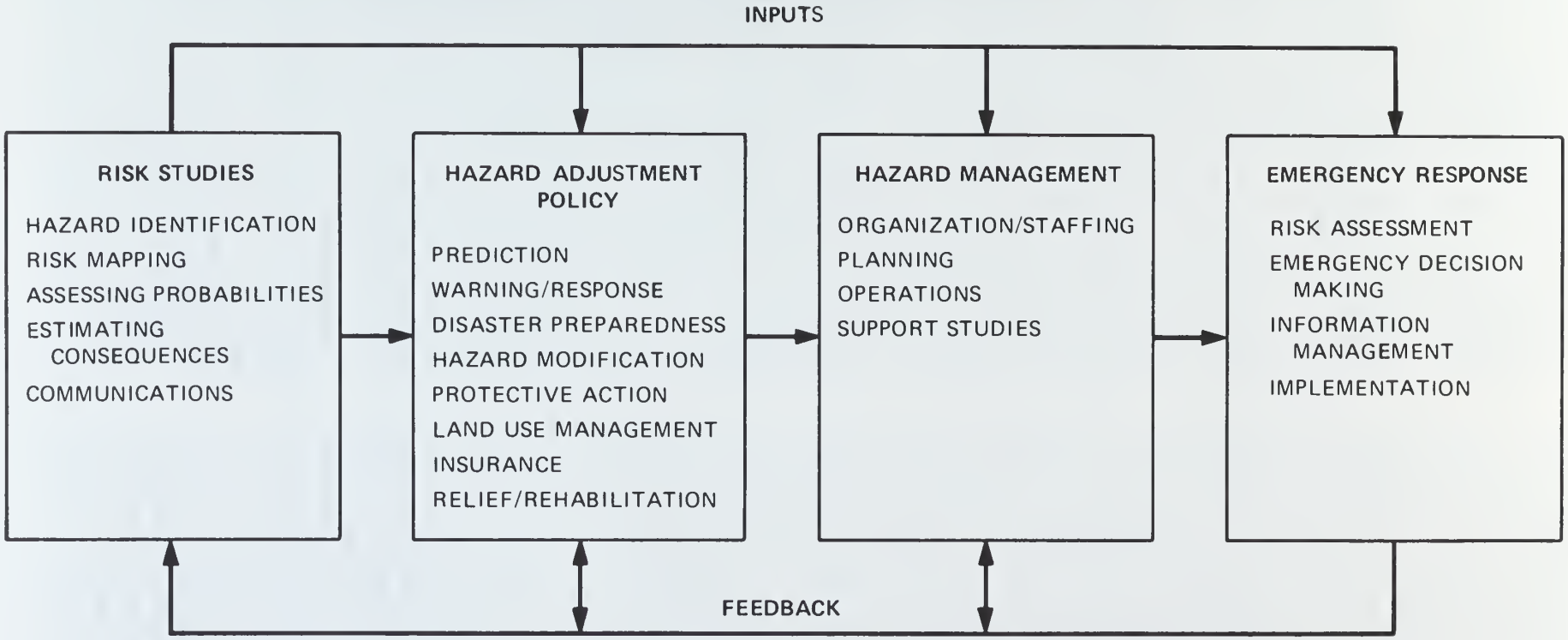


Figure 1. A framework for volcano hazard management.

approach and not piecemeal strategies or isolated preparedness plans (White and Haas, 1975). A broad-based program is not necessarily expensive or grandiose. States embracing a "comprehensive" all-hazards approach to emergency management, such as the one developed by the National Governors' Association, should be able to integrate volcano-related activities into a broader and interactive process (Whittaker, 1979).

A four-phase scheme of volcano hazard management is outlined in Figure 1. This scheme is an attempt to integrate long-range crisis management with short-term crisis response. In doing so, it integrates the risk assessment approach suggested by Warrick (1975, 1979) with a warning preparedness capability (Sorensen and Gersmehl, 1980; Mileti and others, 1981). The chief goals of this approach are to reduce the likelihood of damages to some "acceptable" level while remaining capable of responding to a threatening or damaging situation.

The first task of management is developing a base of risk information to guide policy and response. Second, a policy must be formulated to specify what actions or "adjustments" should be utilized in a management system. Third, that system must be organized to plan and prepare for a potential emergency. Finally, a mechanism is needed to respond to an eruption when a clear threat emerges.

Risk Studies

The subject of risk studies was extensively covered yesterday by the earth scientists. To me this is a vital part of framing a comprehensive program. Without the risk assessment and prediction work that geologists are doing, there would be no need to meet here today. Risk information guides the formation of hazard management policies and response strategies (Kates, 1978; Burton and Whyte, 1980). The accuracy of this information and its use can, in pragmatic terms, spell the difference between a catastrophe and an anomaly of nature. In essence, risk studies lay the foundation for a comprehensive management program.

Risk studies supporting volcano hazard management involve the processes of hazard identification, probabilistic assessments, consequence estimation, hazard mapping, and communications (Warrick, 1979).

Specific hazards vary among individual volcanoes or groups of volcanoes (Warrick, 1975; MacDonald, 1975). For example, some volcanoes present hazards from pyroclastic flows, tephra or ash falls, and mud flows; other volcanoes may be more likely to produce lava flows, gases, and explosions.

It is not always possible to predict the manifestations of specific hazards with precision. On the island of Hawaii, where lava flows pose the chief hazard, it has been noted that massive fatalities reportedly occurred in the 1700s as a result of gas emissions from an eruption of Kilauea. In the Mount St. Helens eruption of May 18, 1980, unanticipated horizontal blast forces caused significant damage.

A lack of understanding of the processes that cause eruptions, coupled with the infrequency of eruptions, makes the assessment of the likelihood of an eruption and of the magnitude of associated hazards a difficult task. Even if risk studies can assign a likelihood, the uncertainties are often so great that meaningful decisions based on this information are difficult to make. Thus, when U.S. Geological Survey (USGS) scientists observed in 1975 that Mount St. Helens would possibly erupt before the end of the century (Crandell and others, 1975), it is not surprising that emergency managers paid little heed. Conversely, the revision of probability of an eruption of Mount Baker in 1975 from 0.001 to 0.01 (chance in one year) led to drastic actions by officials, despite public protest (Hodge and others, 1979).

The potential consequences of hazard -- whether physical, social, economic, or psychological -- help determine the levels of risk that societies face from volcanic eruption. Consequences are determined by three factors: hazardous events, human exposure, and human response. Perhaps the most challenging aspect of risk studies is to integrate geologic knowledge with demographic and behavioral information to estimate potential

losses and damages. Given today's imperfect information and the various permutations of possible events and future societal change, accurate estimations of consequences from eruptions are, at best, crude approximations. Despite such difficulties, USGS studies of the hazards of a potential eruption at Mount St. Helens (Crandell and others, 1978; 1979) proved fairly accurate, given the range of possible effects and outcomes (Sorensen, 1981b).

If such was the case, why did serious losses result from the May 18 eruption? Utilization of risk studies depends primarily on the ability to map hazards and to communicate risk information to emergency managers and to those potentially affected by the hazards. For the volcano Kilauea in Hawaii, this has been relatively simple. Scientists have delineated the paths of potential lava flows and, once an eruption occurs, they can provide reasonable estimates of the areas of risk. Mount St. Helens proved less predictable. Despite the availability of good risk maps, people exposed to tephra falls received little advance warning of the potential impacts of a fall or information on appropriate response patterns (Saarinen and Sell, 1981). The problem of communication leads, in turn, to other phases of emergency management.

Adjustment Policy

The success of coping with any single eruption will be, in part, determined by the nonemergency activities of emergency managers. Following a disaster, it is often recognized that a variety of options were available that would have reduced losses, yet, only a few were employed, at perhaps suboptimal levels. The formulation of an adjustment policy which emphasizes a diverse set of options can help avoid such predicaments (White and others, 1958; Burton and others, 1978).

Theoretically a wide range of actions can be utilized to manage volcano hazards (White and Haas, 1975; Warrick, 1975). Prediction involves forecasting the behavior of the volcano and associated hazards. Warnings inform people of an appropriate response to take that will reduce the likelihood of losses from hazard. In some cases, volcano hazards can be modified once an eruption occurs. For example, bombing, diversion barriers, or water cooling have been employed to divert or impede flows (MacDonald, 1972). Protection covers those actions to prevent consequences of hazard: using masks to filter out ash, shoveling ash to prevent roof collapse, or using excess reservoir capacity to hold back mudflows are examples. Land-use management guides human development away from potentially hazardous locations. Volcano risk studies, however, have not always been available nor precise enough to practically or legally make such decisions. Insurance can be utilized to compensate persons or organizations for losses incurred, as can relief/rehabilitation programs. It was interesting that at Mount St. Helens there were a lot of people talking about earthquake insurance that would cover any losses that occurred from the eruption of Mount St. Helens. I don't believe there is any insurance that covers volcanic damages -- although it was once pointed out to me that you could buy volcanic hazard insurance east of the Mississippi River. [Laughter.]

Adjustment policy includes choosing the appropriate mix of actions, determining how to implement them, and establishing where and when they apply. These decisions should take into account the best available risk information, but, ultimately, they must involve value judgments and expert opinion. A myriad of difficult ideological questions concerning acceptable risks enters into setting adjustment policy (Burton and Whyte, 1980). As yet, an "optimal" adjustment policy for any hazard has not been proven, and, indeed, evidence of inappropriate policies abounds. Even if an optimal policy could be determined, it would not necessarily guarantee effective management. Ultimately, it is the implementation that determines success or failure.

Hazard Management

The goal of hazard management is to link risk studies with adjustment policy to form effective loss-reduction mechanisms. It includes both long-term planning and short-term crisis response functions and

integrates them into a comprehensive program. Important components of hazard management include organization, planning, operations, and supporting research.

With regard to risk studies, we can ask questions like, "Why wasn't more done with respect to emergency planning in light of the publication of the Crandell and Mullineaux findings about Mount St. Helens? Conversely, in 1975, when the USGS revised the probabilities that Mount Baker would erupt, why did people in the area, according to the study conducted at the University of Washington, feel that public officials were totally over-reacting to the situation? These examples underscore the problem of translating risks studies into appropriate hazard management.

Accordingly, it is important to place volcano management in an organizational structure which will ensure that authority and responsibility are firmly established and provide for managerial continuity. The Mount St. Helens experience revealed that volcanic activities were not an integrated part of state emergency management concerns and activities in Washington (Sorensen, 1981a). The lack of coordination created interjurisdictional uncertainties.

One thing we learned from Mount St. Helens is that the lack of hazard management structure can be a definite problem in the initial response to a threatening event. Of course, this is not really unique in the sense that has been mentioned; volcanoes are rare events, so why should we be concerned with them? Some of the data I collected supports this notion. In interviewing various organizations involved with the emergency response effort in the several weeks following the initial eruption of March, the results indicate (Table 1) that not too many people put much effort into preparing for the volcanic eruption. The urgency of preparation, or lack thereof, explains why no one prepared, for most of the organizations stated that it was not really too important in their overall mission to prepare for an event like this. On the other hand, they recognized the fact that, indeed, they have some or a lot of unique responsibilities to carry out in this situation, so we find a complexing paradox here. It's not important to prepare, yet, there was need to prepare, but this preparation didn't come about. This illustrates one of the problems of long-term hazards management.

Proper management includes both planning and operational capabilities. It is the role of the planner to translate risk studies and adjustment policies into practicable actions, such as the development of land-use regulation or the design and testing of warning systems. Management also means being able to switch from a long-range planning mode to an operational mode when geophysical evidence suggests a possible eruption. In both cases, there must be close cooperation between the risk analysts and the emergency managers.

Finally, emergency management should be supported, when financially feasible, by studies which evaluate and improve response capabilities.

Periodic assessments by the Hawaii County Civil Defense have resulted in improvements in their response procedures (Sorensen and Gersmehl, 1980).

Emergency Response

Emergency response is integrally tied to the other three phases of hazard management. Figure 2 attempts to systematically characterize the functioning of a volcano-hazard emergency response system; it can apply in concept to other hazard management problems. A volcano may be subjected to a variety of geophysical monitoring systems. Scientists may be charged with monitoring data to detect anomalies which may be precursors of an eruption. When such occurrences are noted, they are then in the difficult and unenviable position of assessing risks and predicting the future behavior of the volcano. The first critical set of decisions involves the communication of technical information about the volcano, its risks, and its expected behavior, to other affected and interested persons.

Working with scientists are the public officials charged with managing governmental and public response. Their chief responsibility, of course, is maintaining

TABLE 1

PREPAREDNESS

A. EFFORTS TO PREPARE

	Very Great	Some	Not Very Much	None
Total number of organizations	2	2	2	8
Type				
Emergency response	1	1	0	3
Support	1	1	0	4
Communication	0	0	2	1

B. IMPORTANCE OF PREPARATION

	Very Important	Fairly Important	Not Very Important	Not Important at All
Total number of organizations	4	1	2	7
Type				
Emergency response	1	1	1	2
Support	3	0	0	3
Communication	0	0	1	2

C. UNUSUALNESS OF RESPONSIBILITIES*

	None	Some	A Lot	Total
Total number of organizations	2	5	5	12
Type				
Emergency response	0	3	1	4
Support	0	1	4	5
Communication	2	1	0	3

* Two organizations did not answer.

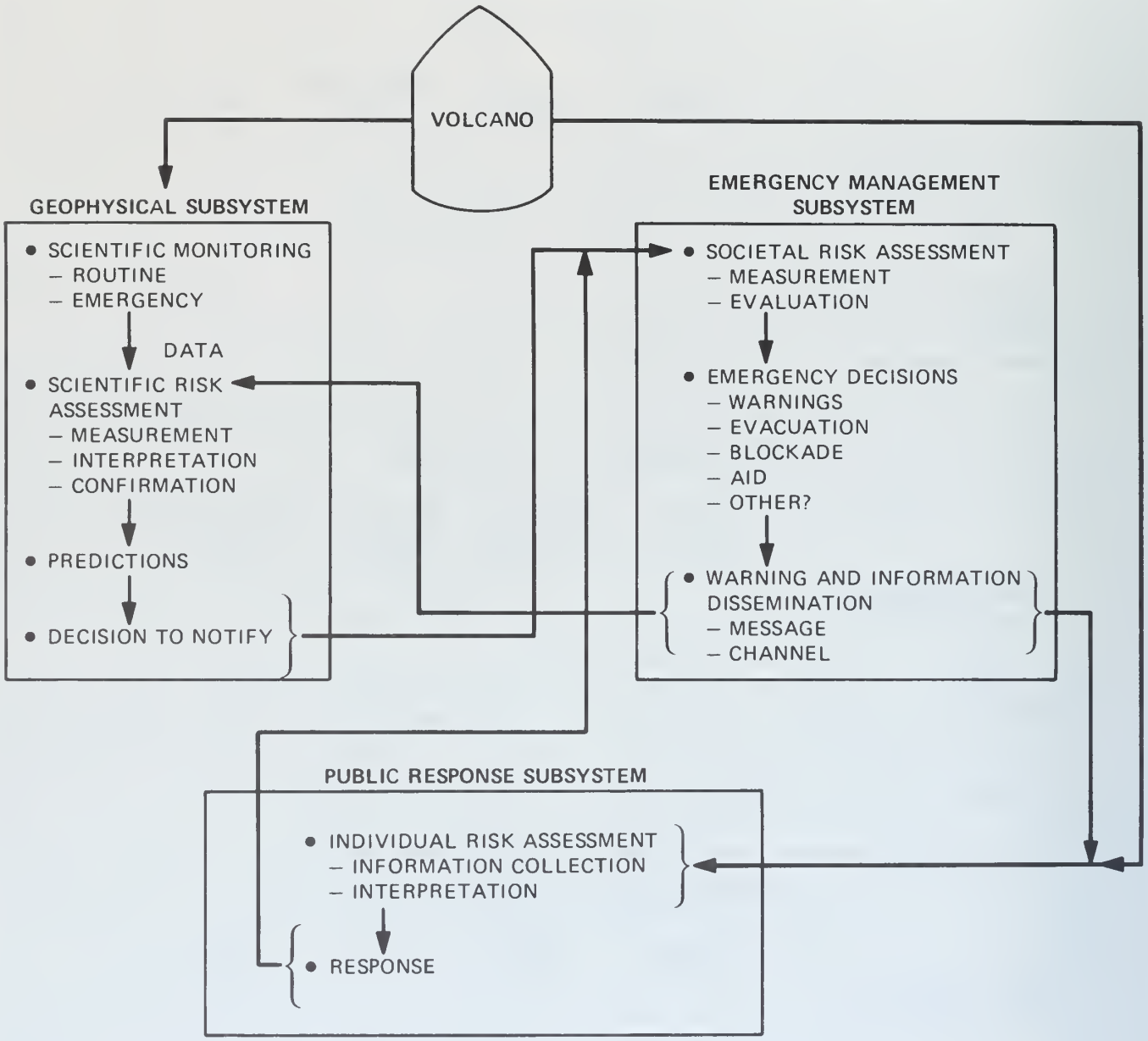


Figure 2. Emergence Response System.

public safety, a goal often hampered by considerations other than the technical advice given by scientists or other advisors. A good illustration of this was the roadblock situation. In the first few weeks after the eruption, there was a real tug of war over where these roadblocks were placed. Figure 3 is a road map around Mount St. Helens. The first roadblock was placed at Camp Baker, and then it was moved up to the county line position (No. 2) so that, as Les Nelson will probably tell you, Cowlitz County and Skimania County personnel could jointly man the roadblock. Then, it shifted back to position 3, because the scientists said it was risky to have it so close to the volcano. Then, the loggers from Camp Baker, the Weyerhauser Company, started putting pressure on emergency response people, and they shifted it up above Camp Baker again. At this location, the crowds became such a problem, they then moved the roadblock farther away. The same thing essentially happened south of the volcano. As illustrated by Figure 4, the roadblock was placed all the way down to Jack's store. The owners were probably very happy about this because it made them a lot of money, but because people in Cougar complained, it was returned. Thus, we saw a lot of disaster-related decision making that had very little to do with the risk assessment activities that were going on at this time. Officials representing a range of agencies and organizations with formal and ad-hoc authorities faced the continual barrage of problems which required emergency decisions. To warn or not, evacuate or stay, block roads or allow access, seek aid or foot the bill -- all are examples of critical choices which were not always easy to make and which were complicated by factors outside the realm of geology.

Finally, it must be recognized that the public is a key component of the management system. Ultimately, their decisions determine, in part, whether a disaster has occurred on a societal level or on an individual one, and whether individuals are victims of the event. To help illustrate these points, several specific problems experienced at Mount St. Helens are reviewed.

SPECIFIC EMERGENCY MANAGEMENT PROBLEMS AT MOUNT ST. HELENS

Responsibility and Liability

During the emergency, questions regarding responsibility for public safety emerged; for example, who would control the roadblocks on federal, state, and county highways. There were also some immediate problems regarding dam safety, the risks, and also the costs. Fortunately, Swift Reservoir was down 125,000 acre feet, so it didn't present an immediate problem. Emergency powers and their responsibility emerged as a major issue. Exactly what authority did the government have to make certain kinds of decisions such as to keep people out of the "red zone," and conversely, what kind of liability did they have for the situation? It was interesting that people were required to sign a waiver upon entering risky areas, yet, this was apparently done in ignorance of the fact that, in the State of Washington, people can't sign away their rights to litigation, so essentially the releases were meaningless. Financing was a related problem at the time. Many of the emergency decisions centered around the questions -- who pays? Who foots the bill? And, how much will it cost?

Communication

A significant problem in emergency management was communication. Figure 4 is an attempt to detail the flow of information during those several weeks after the first eruption, and show some of the relationships between various organizations and how information and directions were passed down. Some organizations, such as the State Department of Emergency Services, were pretty far removed from the line of communication. A result of this is that the other state agencies really didn't know what was going on. In the course of a discussion I had with the Governor's aide, who was handling the situation for the Governor, it was revealed that the executives had little information on the situation and were unclear about how to respond. Based upon

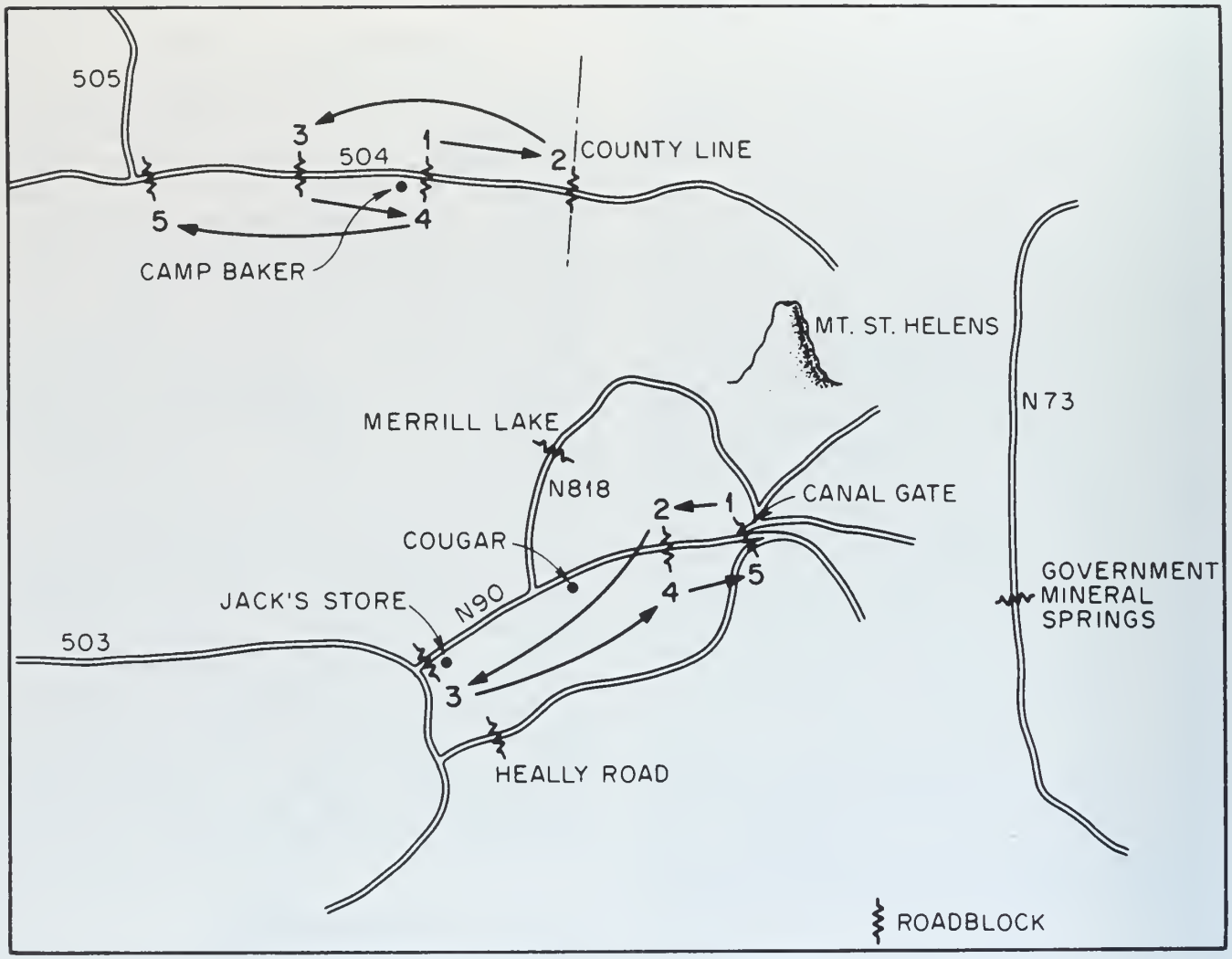


Figure 3.

ROAD BLOCKS

Road	Date	Location	Type
504/1	3/25	Camp Baker	Advisory only
/2	3/27	County line	Manned by County
/3	3/27	10 miles west of County line	Manned by County
/4	3/28	Camp Baker	Manned by County
/5	4/4	Junction W/505	Manned by State
503/1	3/25	Swift Reservoir Gate	Unmanned
N90 2	3/27	3 miles above Cougar	Manned by County
3	4/5	Jack's Stove west of Cougar	Manned by National Guard
4	3/8	3 miles above Cougar	Manned by Sheriff
5	3/10	Swift Reservoir Gate	Unmanned
N818	3/28	Merrill Lake	Manned
N73	3/28	Government Mineral Springs	Manned
Healy Road	3/28	West of Chelutchie	Manned

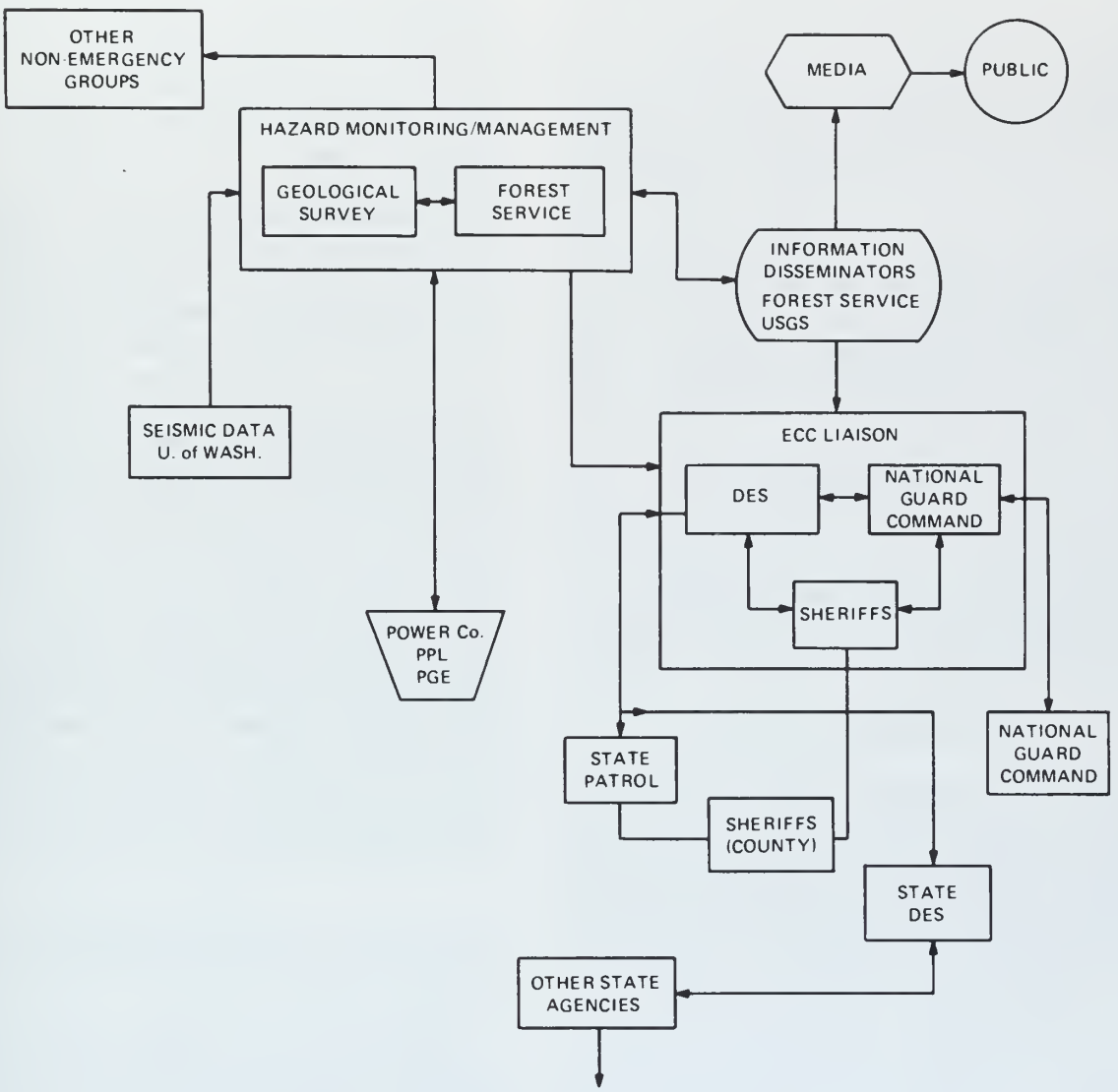


Figure 4. Early information flow at Mount St. Helens.

further discussion, the reason for this appeared to be that they just weren't getting the type of information which they could readily understand. A number of people we talked with, involved in the organizational structure, stated that the lack of understandable information about what was going on, as for example, the concrete predictions that we have been talking about here, were lacking, and thus, a lot of uncertainty was created. Some of that uncertainty was reflected in the kind of information that was going out to the public. I examined most of the lead articles in several local newspapers every day, from a period of March 21 through April 11, and tried to ferret out from them whether they were saying (1) eruptions are more likely, (2) we don't know what is going on, or (3) eruptions are less likely. There seemed to be a flip-flop in the information the public was getting. Some days, it was reported that an eruption was likely, but the next day, it wasn't clear. Once there was an article saying it was certain that the volcano would stop erupting in the near future, and so forth. This was not reflective of the information geoscientists were giving out. They were merely reporters' interpretations or opinions.

Conflicting Opinions

There was uncertainty about some of the safety aspects of the various volcano hazards. In analyzing the same set of lead articles, it was found that they contained conflicting statements regarding threats or damages from the eruption. Some said, "worry about ash fall"; others stated ash fall was not a problem. Thus, people were getting conflicting information from the media.

Finally, looking at the same articles with respect to some human response themes, there was some concern with evacuation and what to do. But, by far, the overwhelming number of articles were on how people were converging on the scene and where you could go to find a nice spot to view the volcano. Much media attention was given to people, such as Harry Truman, who were defying the risks. Thus, it appears that the public (based upon the media sources analyzed) was receiving very confusing information about what to do, and I think this was reflected later on in what happened on May 18.

Convergence Population

One hundred twenty persons who had converged on the area were questioned. One of the things asked was: You are in the vicinity of a volcano; what do you want to see it do? Not surprisingly, a lot of people wanted see the "big one." I don't think they imagined what the consequences of that would be. Some people wanted just more minor entertainment in the form of small eruptions, and I think those people were factoring into their answer the fact that some people would likely be hurt by a major eruption. Finally, a lot of people that lived in the area wanted the whole volcanic threat to go away. This survey provided some interesting insights into what was going on in people's minds as they converged into a hazardous area. These responses, by the way, were collected in Cougar, which wasn't a very risky location. We know from other studies that most people who expose themselves to this risk don't feel too threatened by it because of the "It can't happen to me" attitude. Furthermore, this data indicated that no one thought that a damaging eruption was certain. At that time, most people didn't think that a major eruption was likely. These are just some of the insights gained from the studies.

LEARNING FROM EXPERIENCE (RECOMMENDATIONS)

Because volcanic eruptions are relatively infrequent, vary considerably in their characteristics, and affect dramatically different social settings, it is somewhat dangerous to generalize from past experiences. Nevertheless, eruptions of Kilauea and Mount St. Helens hold valuable lessons for the emergency manager.

A brief review of the behavioral science research on volcanoes cited in this paper, coupled with the very recent field research described above, leads to the following observations and recommendations.

Risk Determination

a. Detailed risk information makes the emergency manager's tasks much easier and more credible, despite the fact that uncertainties cannot be eliminated. The current efforts by the USGS to map volcano hazards is extremely valuable and should be pursued at an accelerated pace. The use of geographic information systems coupled with computer mapping techniques should be investigated to improve mapping procedures.

b. A major problem with risk studies is the difficulty of portraying credible and imaginable portraits of the consequences of hazards. Innovative means are needed to present risk information in an interpretable and impressive fashion.

c. Probabilistic frameworks have been only marginally useful in framing volcano hazard management policies and decisions. The low probabilities usually associated with eruptions are not meaningful in forcing decisions which appear to be insensitive to such low numbers. Risk studies that focus on how the likelihood of eruptions changes on a short-term basis would appear to be more valuable in their line of approach than studies that forms on frequency of eruptions in geologic time.

Adjustment Policy

a. To date, there has been little focus on viewing volcano management in a long-term planning horizon. The emphasis has been on crisis response rather than adjustment. A redirection of effort may be warranted.

b. Relief practices have overshadowed insurance options for compensating victims of volcano hazards. Added considerations should be given to integrating volcano with earthquake insurance.

c. Localities exposed to potential volcano risks should learn from Hawaii's experience that preparedness plans are valuable in guiding response activities. Even if plans sit on the shelf, a dusty plan is better than no plan at all.

d. Further attempts to integrate prediction with warning capacities should be investigated. A quick-response capability to begin early monitoring of a volcano that shows unexpected activity would be useful.

e. An integration of land-use planning efforts for flood plains with planning for mudflows might be a prudent means for initiating the application of this adjustment to volcano risk.

f. As suggested by Warrick's findings (1981), the relationships between adjustments for other hazards or crises and volcano management should be explored in a systematic way.

Hazard Management

a. The absence of a hazard-management structure with clear lines of authority and delineation of responsibility was a problem at Mount St. Helens (Sorensen, 1981b). This can be easily avoided through minimal planning efforts prior to an emergency.

b. Federal emergency response capabilities and authorities are geared toward disaster response and not to pre-disaster threatening situations. FEMA should be given authority to assist in a volcanic eruption emergency, if needed, before major damages occur.

c. Volcano management should be integrated into a comprehensive planning scheme at local and state levels where appropriate. The National Governors' Association provided a useful model for accomplishing this task (Whittaker, 1979).

Emergency Response

a. A major problem, and probably the most difficult task of emergency response, seems to be the communication of volcano hazard warnings and risk

information to the public. This is not a unique difficulty, but it is vital to reducing losses from hazard, and warrants improvement.

b. Eruptions are magnets for people. Controlling convergers is the second most difficult task for managers and requires careful pre-eruption planning.

c. As for long-term management, a response mechanism requires clear delegation of authority to avoid confusion and competition.

d. Since volcanic eruptions are rare events in many locations, emergency managers cannot be expected to be well-prepared to respond in the event of an eruption. A means for rapid mobilization and education when an eruption is imminent would be a valuable step in switching from management to response operations.

CONCLUSIONS

Planning for rare events is difficult in light of the many more pressing problems of society. Risk assessment methodology may help sort out priorities and establish desired programs and policies, yet it cannot be viewed as a panacea. An alternative program could be based on a minimum safety approach in which minimal preparations are made, capabilities for expanding efforts into an emergency-response mode are developed, and volcano hazard management is closely tied to other hazard programs to benefit from overlapping concerns.

When looking back to the May 18, 1980 eruption of Mount St. Helens, one tends to think in terms of what could have happened without the competent efforts of emergency managers. No doubt emergency planning and response activities initiated at the end of March were instrumental in reducing losses. However, circumstantial factors, such as the time of day that the eruption occurred, the season, and the availability of response capabilities for hazards such as snow or drought, were also critical in reducing the toll. In reality, luck was on the emergency management's side. Randomness may work in the opposite direction the next time.

DISCUSSION

Comment from the floor: As early as 1974, the Washington State Department of Emergency Services had a fairly detailed report compiled by myself and others, including Rocky Crandell and Jack Hyde and others, that fairly well outlined the volcanic risk zones for the State of Washington, what kinds of hazards to expect, and the areas in which to expect them, the types of things that cause damage and loss of human lives, and how to determine "red zone" boundaries. They had a great wealth of information already in their files, and when they were asked about it, they came up with any of three answers: 1) We didn't know it was there; 2) We know it's there, but we didn't know where to find it; and 3) We knew it was there, we looked at it, but we didn't believe it.

John Sorensen: Thank you for underscoring some of the points I was trying to make.

James Davis: Can you comment on the public reception of various terms such as "hazard watch," "hazard alert," etc. used by the USGS?

John Sorensen: At the time I was doing my study, I don't recall hearing those terms by the USGS. I think, when you use jargon with a special definition, as, for example, "active volcanoes," it's going to create certain kinds of confusion in the public. Experience with other hazards such as hurricanes and tornadoes show people do not always understand and make distinctions between special phrases. They tend to form images of what they think the words mean that are different from those of the officials' using them. There are certain difficulties in using such phrases, but no real good solution or alternatives to the problem.

REFERENCES CITED

Burton, I., and Kates, R., 1964, The perception of natural hazards in resources

management: Natural Resources, v. 3. p. 412-441.

Burton, I., Kates, R., and White, G., 1972, The environment as hazard: Oxford University Press, New York.

Burton, I., and Whyte, A., 1980, Environmental risk assessment: Wiley, New York.

Crandell, D., Mullineaux, D., and Miller, C.D., 1979, Volcanic-hazards studies in the Cascade Range of the Western United States, in Sheets, P., and Grayson, D., editors, Volcanic activity and human ecology: Academic Press, New York.

Crandell, D., and Mullineaux, D., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C.

Crandell, D., and Mullineaux, D., and Rubin, M., 1975, Mount St. Helens' volcano -- recent and future behavior: Science, 187, 438-441.

Fischoff, B., Slovic, P., and Lichtenstien, S., Lay fables and expert foibles in judgments about risk, in O'Riordan, T., and Turner, R., editors, Progress in Resource Management and Environmental Planning, v. 3, Chichester: Wiley, forthcoming.

Hodge, D., Sharp, V., and Marts, M., 1979, Contemporary responses to volcanism: Case studies from the Cascades and Hawaii, in Sheets, P., and Grayson, D., editors, Volcanic activity and human ecology: Academic Press, New York.

Kates, R., 1962, Hazard and choice perception in flood plain management: University of Chicago, Department of Geography, Research Paper No. 78.

Kates, R., 1978, Risk assessment of environmental hazard: Wiley, New York.

MacDonald, G. A., 1972, Volcanoes: Prentice-Hall, New York.

Mileti, D., Hutton, J., and Sorensen, J., 1981, Earthquake prediction response and options for public policy: University of Colorado, Institute of Behavioral Science.

Saarinen, T., and Sell, J., 1981, The role of agency perceptions in warning about the Mt. St. Helens eruption: Paper presented at the Fourth Applied Geography Conference, Tempe, Arizona.

Slovic, P., Kunreuther, H., and White, G., 1974, Decision processes, rationality and adjustment to natural hazards, in White, G., editor, Natural hazards: local, national global: Oxford University Press, p. 187-204.

Sorensen, J., 1981a, Decisions in emergencies: A comparison of volcano hazard in Hawaii and the Cascades: Paper presented at the Fourth Annual Applied Geography Conference, Tempe, Arizona.

Sorensen, J., 1981b, Emergency response to the Mount St. Helens eruption: University of Colorado, Institute of Behavioral Science, Boulder, Natural Hazards Working Paper No. 42.

Sorensen, J., and Gersmehl, P., 1980, Volcanic hazard warning systems; persistence and transferability: Environmental Management, v. 4, p. 125-136.

Warrick, R., and others, 1981, Four communities under ash: University of Colorado, Institute of Behavioral Science, Boulder.

Warrick, R., 1979a, Volcanoes as hazard; an overview, in Sheets, P., and Grayson, D., editors, Volcanic activity and human ecology: Academic Press, New York.

Warrick, R., 1975b, The volcano hazard in the United States; A research assessment: University of Colorado, Institute of Behavioral Science, Program on Technology, Environment, and Man, Monograph No. NSF-RA-E-75-012.

Whittaker, H., 1979, State comprehensive emergency management: National Governors' Association, Washington, D.C.

White, G. F., and others, 1958, Changes in urban occupance of flood plains in the United States, University of Chicago, Department of Geography, Research Paper No. 56.

EMERGENCY PLANNING IMPLICATIONS OF LOCAL GOVERNMENTS' ADAPTIVE RESPONSE TO MOUNT ST. HELENS

Jack D. Kartez[1]
Environmental Research Center
Washington State University

ABSTRACT

A rapid response research investigation was conducted one month after the May 18 eruption of Mount St. Helens to document implementation of emergency measures by local governments receiving ash fallout. It was believed this data might later prove useful in evaluating the design of disaster response plans for hazards impacting large areas, such as major earthquakes and radiological emergencies. Social scientists have suggested that disaster response effectiveness can be enhanced by understanding the actual pattern of behavior in emergencies. This study collected data relevant to determining if such suggestions by social scientists are viable for the real-time decision-making of public officials in an unexpected emergency. A further objective was to identify specific organizational and logistical problems which are inherent to multi-jurisdictional emergencies, and the adaptive local government response to these factors.

A written survey of 26 jurisdictions was conducted, with detailed on-site follow-up interviews in 12 of the jurisdictions. The results, although tentative, illustrated three phenomena important to effective disaster planning: (1) ad-hoc, adaptive decisions by public officials included response strategies which were highly similar to concepts suggested by social science researchers; (2) emergency coordination plans and statewide resource support systems were less often useful than normal public management organization and local adaptation in securing needed equipment and manpower resources and public cooperation; (3) several problems inherent to multi-jurisdictional emergencies -- such as overlapping communications and competition for resources -- appeared to be unanticipated in emergency preparedness within the study area, which covers subregions of three states.

Among the implications of this study's observations was evidence that the countywide emergency coordination system encouraged by state and federal programs lacks direct linkages with the local government public works and city management personnel who must organize resources and citizens in emergency. Another implication is that existence of ongoing community development or general planning activities which organize citizens may enhance success of emergency response measures.

---

[1] Assistant Professor of Environmental Science and Regional Planning, WSU, Pullman WA. Professor William Kelley of Eastern Washington University, Cheny, was Consulting Investigator for this research. This work supported by National Science Foundation Grant No. PFR 8020876. The views expressed herein are the author's and do not necessarily represent those of the National Science Foundation or Washington State University.

INTRODUCTION

The May 18, 1980 eruption of Mount St. Helens deposited as much as 5 inches of volcanic ash within a 20,000 square mile area. While national attention focused on the destruction at the mountain, dozens of communities in the plume path were responding to severe problems caused by the ash. This was compounded by the virtual isolation of communities as transportation ground to a halt in choking clouds of ash. A rapid response research investigation was conducted one month after the May 18 eruption.

This research analyzed the operational experience of local governments responding to the emergency created by the ash fallout. Information was collected on the actual strategies local governments adopted to organize their resources, seek outside assistance, and work with their citizens. It was believed this data might prove useful in the future evaluation of response plans for hazards impacting large areas, such as major earthquakes and radiological emergencies. But our investigation did not arise out of ongoing disaster research. As policy planners, we were motivated by very recent work on the subject of "research-based community emergency planning" conducted by sociologists. A brief elaboration on this will help explain the concepts and questions underlying our investigation and the context in which we have sought to draw lessons from Mount St. Helens.

DISASTER RESEARCH AND PLANNING THEORY

Social scientists studying disaster have argued that population behavior in emergencies has a regular pattern. They believe public authorities must recognize these behavior patterns when designing response and recovery plans, because:

> Too often emergency plans which are administratively devised turn out to be based on misconceptions of how people react and, therefore, potentially create more problems than they solve (Perry 1979).

Social scientists argue that research insights can enhance the effectiveness of response if they are only incorporated into plans by the authorities. They have suggested specific strategies to overcome common problems in implementing disaster response, such as unwillingness to evacuate ("warning confirmation behavior") and jammed telephone lines ("convergence behavior"). In each case these strategies are built around people's known reaction patterns and provide incentives for them to comply with an organized response plan. For example, several researchers suggest making positive use of the telephone to combat confirmation and convergence by establishing central hazard confirmation phone centers. One strategy involves people-oriented grapevines or phone trees wherein authorities would first contact selected residents who pass on information in their immediate areas (Holgate 1978).

These concepts made a great deal of sense to us as planners. The history of planning is filled with ineffective programs and policies which disregarded the behavioral basis for community needs. Many urban renewal projects are good examples. We also agreed with criticisms these researchers raised about the tendency to treat disaster planning as a product -- a report on a shelf -- rather than a process (Wenger and others, 1980). That issue cuts through most planning. But there is also a tendency on the part of disaster researchers to treat implementing agents -- or public officials -- as a kind of "black box." Emergency planning offices, general purpose local government, state and federal agencies all tend to be lumped into categorical definitions like the "planners" or the "authorities."

This obscures the operational dynamics of planning and implementing the public emergency response. More attention needs to be given to the complexities of the emergency planning process itself and the unique qualities of the different public institutions involved. Knowledge about disaster planning needs has to be translated into practice through these institutions. John Friedmann calls this linking of knowledge to action the "essential meaning of planning" and its central problem (Friedmann, 1979). The

field of planning is dominated by arguments over this gap between ideal objectives and what it is actually possible to implement.

The planning and community development profession is learning that more attention has to be paid to the institutional problems of implementing policies or strategies of any kind. Even the best of ideas requires facilitation that's sensitive to what Larry Susskind of MIT calls the "situational potentials, institutional constraints and client needs" in each case (Susskind, 1974). The question underlying our investigation was: "Why should emergency response planning be any different?"

OBJECTIVES AND SCOPE

Our first objective was to collect information on the direct operational experience of local governments responding to the ashfall. How did it compare with our normative expectations about how response and recovery ought to be implemented? A second objective was to assess the potential usefulness of the concept of adaptive, behavior-based strategies suggested by social scientists. Thirdly, we wished to identify the institutional and situational constraints faced by local officials.

Time does not permit more than highlights of 40 tables of results, 12 case studies, and some suggestions of possible implications for emergency planning. Three types of activities dominated most jurisdiction's response to the May 18th eruption: organizing local government resources; finding outside assistance, especially heavy equipment; and communicating with citizens, asking them to follow various locally defined strategies. Data was collected through a written, mail-out survey of 26 jurisdictions (Map 1) and detailed, on-site follow-up interviews in 12 of those jurisdictions. This included a sample of jurisdictions in the May 28 and June 12 eruptions. Thirty-eight percent of the respondents were city managers; 43 percent public works directors and 19 percent elected officials, mainly mayors and county commissioners in more rural jurisdictions.

ORGANIZATION OF THE LOCAL RESPONSE: AN OVERVIEW FROM THE WRITTEN SURVEY

In their immediate response, local governments utilized existing functional lines of organization, such as those that public works, safety and management staff use on a day-to-day basis. No more than one-third of the 26 jurisdictions reported using an existing countywide emergency preparedness plan as the source of any one of four types of information needed to organize local efforts to control thousands of tons of the fine ash. About half reported no use at all of a countywide plan, which is the usual centerpiece for state and federally funded general preparedness planning (Table 1).

Jurisdictions were asked to rank the perceived effectiveness of both the internal and external forms of assistance they received during the first week after ashfall. Local governments ranked their "own judgement" and the private news media as the most useful tools during the immediate response period. Law enforcement communications systems ranked closely behind. Assistance from other cities and counties also ranked highly as sources of assistance. State government ranked last. (Table 2)

Eighty-five percent of the jurisdictions found it necessary to seek equipment resources from an outside source. The major equipment sources were private contractors and other local governments outside the impact area (Table 3). Citizen volunteers were also a source of emergency assistance. Seven jurisdictions reported requesting citizen volunteers, while another fifteen reported some form of spontaneous citizen assistance.

Efforts to communicate with citizens were very central to the local response. Ninety-six percent reported using communications methods and procedures established by the jurisdiction itself, after ashfall. Only one jurisdiction reported complete reliance on a countywide civil defense emergency broadcast system to relay specific instructions and warnings to citizens. Local radio stations were the predominant communications vehicle for three-quarters of the jurisdictions,

MAP 1

STUDY JURISDICTIONS (JURISDICTIONS INTERVIEWED ARE UNDERLINED)

TABLE 1

REPORTED USE OF "COUNTRYWIDE EMERGENCY PLANS"
TO FIND INFORMATION FOR THE EMERGENCY RESPONSE

TYPE OF INFORMATION	PLAN USED		PLAN NOT USED		NO RESPONSE	
	N	%	N	%	N	%
1. "Where to Get Information on Health Hazards of Ash"	10	37%	17	63%	0	0
2. "Which State Agency to Contact for Assistnace"	7	26%	19	71%	1	4%
3. "Where to Get More Equipment"	8	30%	18	67%	1	4%
4. "How to Use Radio or T.V. Media to Send Messages to Citizens"	5	19%	21	77%	1	4%
MEAN RESPONSE	28%		69%		3%	

TABLE 2

PERCEIVED EFFECTIVENESS OF EXTERNAL AND INTERNAL ASSISTANCE RECEIVED DURING THE FIRST WEEK AFTER ASHFALL

	ASSISTANCE SOURCE	MEAN WEIGHTED* EFFECTIVENESS RATING	MEAN	% OF N-27 RESPONDENTS
1.	"Our own observation and judgement"	8.96	1	100%
2.	News Media (Radio, Television, etc.	6.71	2	78%
3.	County Sheriff or Municipal Police Teletype Net	5.00	3	82%
4.	Other Cities	4.96	4	85%
5.	Other Counties	4.71	5	78%
6.	National Guard	3.78	6	70%
7.	Local University	3.70	7	74%
8.	State Emergency or Civil Defense Agency	3.09	8	82%
9.	State Executive Office	1.90	9	82%

Note: * 10 = Most effective; 1 = Least effective

TABLE 3

SOURCES OF EQUIPMENT ACQUIRED BY LOCAL GOVERNMENTS

N = 23

	N	%[2]
Other Units of Local Government[1]	12	52%
State Agencies	4	17%
National Guard	7	30%
Private Contractors	16	70%
Farmers	7	30%
Local University	2	9%
Sales or Rental Dealers	6	25%

NOTES: [1] Includes cities; counties; sub-county highway, fire and school districts.

[2] Percentage of N = 23 jurisdictions receiving equipment.

TABLE 4

COMMUNICATIONS METHODS USED

N = 27

TYPE OF METHOD	RANK BY NUMBER OF JURISDICTIONS USING METHOD (% of TOTAL IN PARENTHESES)
Local Radio Station	1 (74%)
Non-Local Radio Station	2 (59%)
Information Phones Set Up Locally	3 (48%)
"Grapevines"	4 (41%)
Public Address Systems on Vehicles	5 (41%)
Non-Local T.V. Station	6 (37%)
Local T.V. Station	7 (33%)
Written Leaflet Distributed to Residents	8 (26%)
Citizens Band Radio	9 (26%)

TABLE 5

COMMUNICATIONS METHODS USED
AND THEIR PERCEIVED EFFECTIVENESS

1 TYPE OF METHOD	2 RANK BY FREQUENCY OF JURISDICTION USING METHOD (% OF TOTAL IN PARENTHESES)	3* RANK BY WEIGHTED MEAN EFFECTIVENESS SCORE (RATING SHOWN IN PARENTHESES)
Local Radio Station	1 (74%)	1 (8.4)
Non-Local Radio Station	2 (59%)	4 (6.6)
Information Phones Set Up Locally	3 (48%	2 (7.3)
"Grapevines"	4 (41%)	3 (6.72)
Public Address Systems on Vehicles	5 (41%)	8 (4.18)
Non-Local T.V. Station	6 (37%)	7 (5.27)
Local T.V. Station	7 (33%)	6 (5.55)
Written Leaflet Distribution to Residents	8 (26%)	5 (6.14)
Citizens Band Radio	9 (26%)	9 (2.71)

NOTE: *10 = Most effective; 1 = Least effective

with non-local radio stations a close second. However, there was significant use of locally-tailored or adaptive communication strategies. Local information phone centers ranked third in use, by half the jurisdictions. Publicly organized citizen "grapevines" were used by 40 percent (Table 4).

However, a different pattern emerged when jurisdictions were asked to rank the perceived effectiveness of these different communications methods. While local radio stations also ranked first in effectiveness, local information phones and "grapevines" ranked second and third respectively, with non-local radio stations dropping to fourth. One other adaptive strategy -- door-to-door distribution of instructions, which had ranked eighth in use, was ranked fifth in effectiveness. Non-local radio and all television media consistently ranked lower in effectiveness than in use (Table 5).

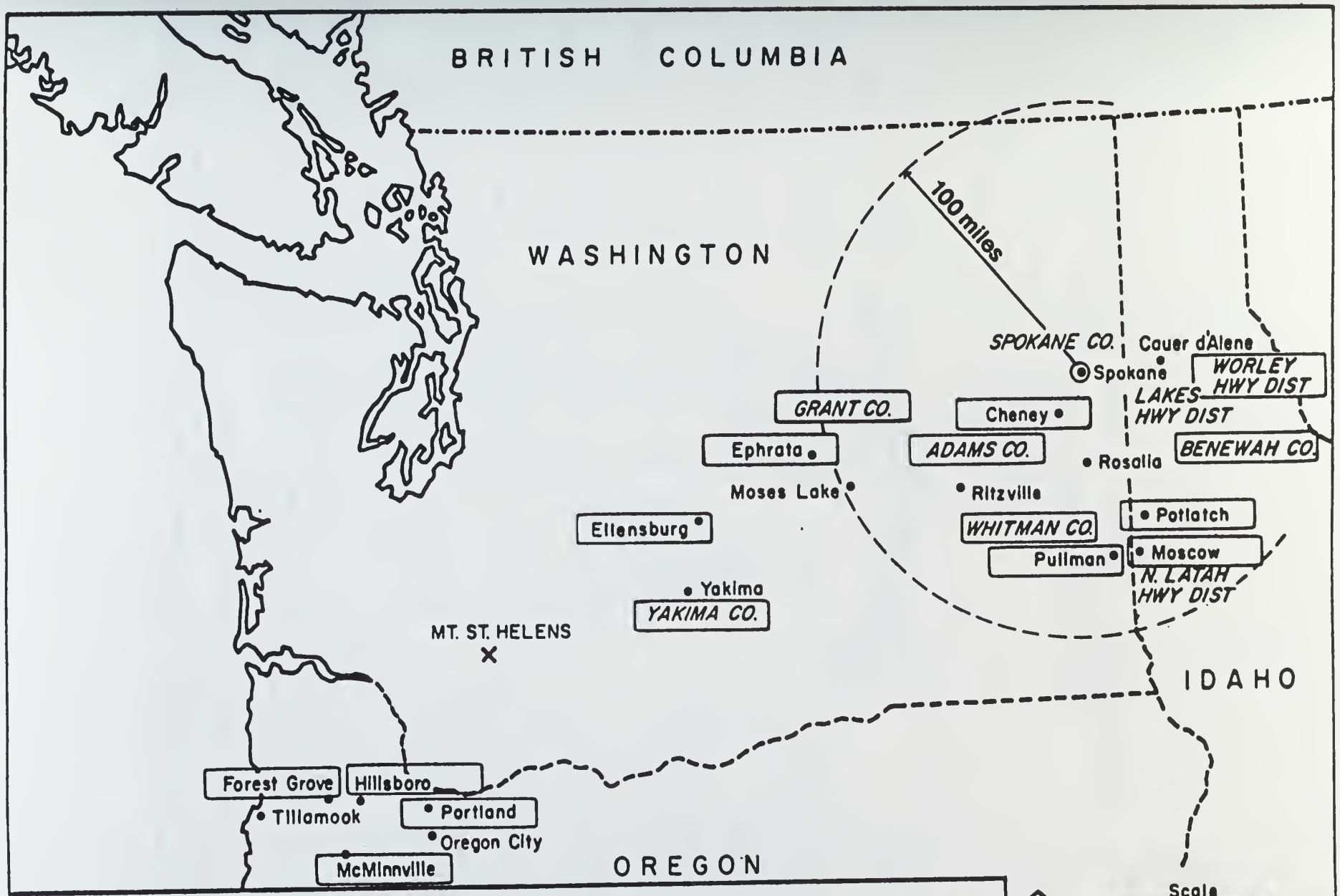
The reasons for this pattern were further revealed by the survey question probing jurisdictions' perceptions of problems reducing media effectiveness as a communications and control tool. Sixty percent or 16 jurisdictions reported problems due to overlapping radio and television messages from larger jurisdictions (Map 2). This means that communities surrounding larger cities like Spokane encountered difficulty in delivering specific instructions to their citizens who were hearing conflicting messages from powerful regional stations. Some jurisdictions also reported other media communications problems such as incorrect messages (44 percent), infrequent broadcasting of public instructions (41 percent) and editing of instructions by media personnel (26 percent). Many of these communities turned to locally controlled adaptive communication techniques such as phone centers and grapevines to overcome these problems (Table 6).

The written survey indicated that local government did not rely on county-wide emergency coordination systems or state government for organization and resources. Without the interview data from the 12 on-site case studies, however, the actual meaning of these general patterns would have been obscure. Although case studies have been subjected to a good deal of criticism in social science disaster research, for such violations of scientific method as subjectivity and non-replicability, their importance cannot be dismissed. (See, for example, the debate between Griffin and Griffin [1975]; and Mileti and others [1975].)

These case studies illuminated how and why local officials engaged in adaptive learning and action planning that was sensitive to the behavior of not only individual citizens but also the behavior of governmental institutions under stress (an area that has received less attention in disaster planning research). A few examples presented here illustrate how local government found equipment through surprising methods, why jurisdictions experienced problems with communications, and how the organization of citizens in a prolonged emergency is related to a much broader set of issues concerning ongoing community planning and problem solving.

FINDING EQUIPMENT

The importance of finding heavy equipment in the ashfall recovery cannot be over-emphasized. The need for water tankers, dump trucks, industrial vacuums, backhoes, and blades outstripped the resources of individual jurisdictions. Private contractors and other local governments were the major sources of this equipment. Although seven of the surveyed jurisdictions were refused equipment by private contractors they normally rely on, the case studies revealed this was a minor problem compared to the hours and days spent negotiating standard rental rates with many separate contractors. Many local governments provided equipment, but this was rarely the result of pre-planned arrangement. Assistance from other jurisdictions did not evolve logically out of geographic closeness or statewide resource allocation. Instead, assistance was based on existing professional ties between public officials, cultural ties between communities, media attention, and the ingenuity of local officials. Assistance came from some distance in many cases, including across state and national boundaries (Map 3).



MAP 2
CASES OF OVERLAPPING MESSAGES FROM RADIO AND TELEVISION NEWS MEDIA REPORTED BY STUDY JURISDICTIONS (IN BOXES)

TABLE 6

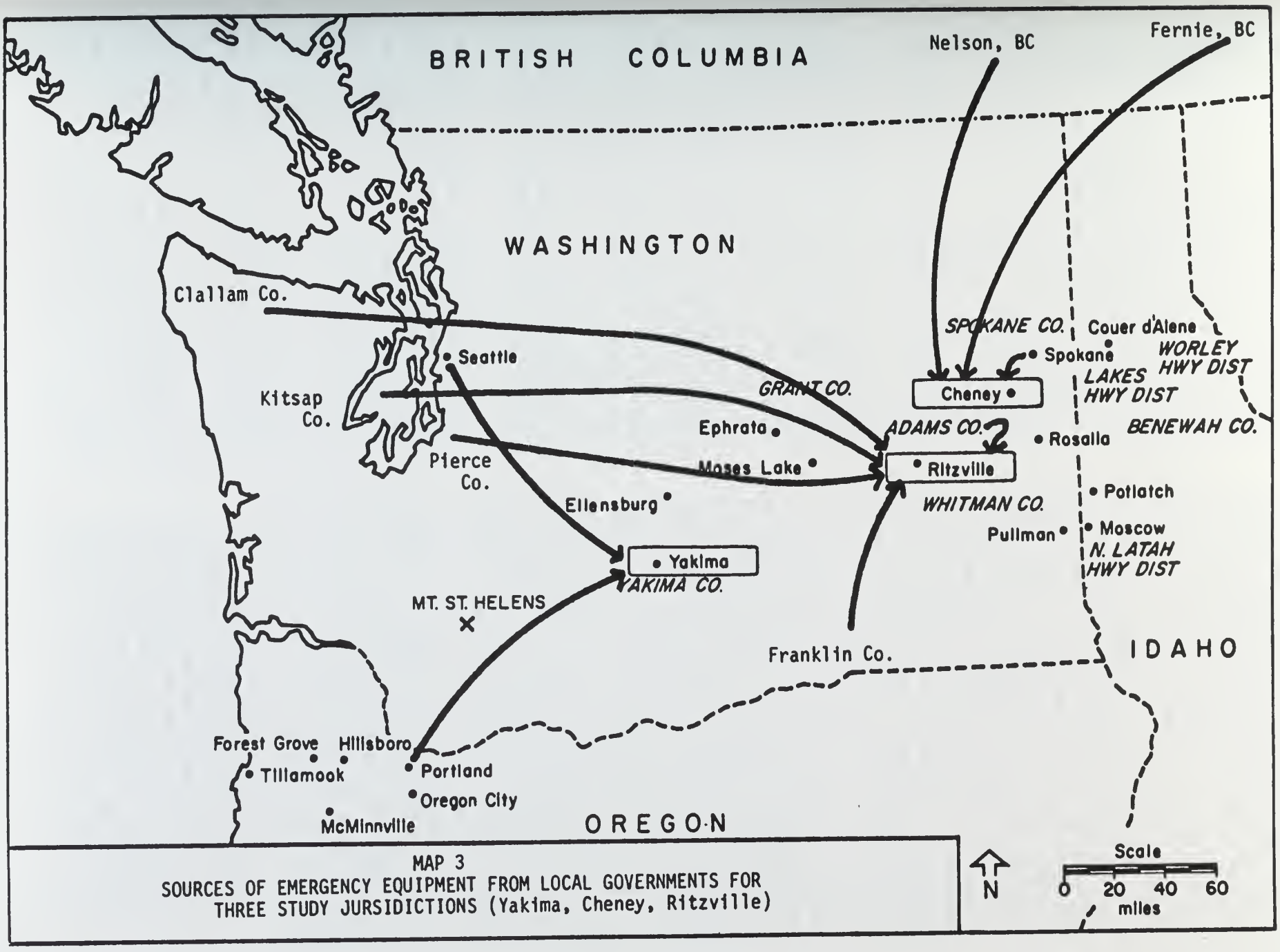
FACTORS REPORTED AS LEADING TO COMMUNICATIONS BARRIERS THROUGH RADIO AND TELEVISION NEWS MEDIA

N = 27

	FACTOR[1]	A REASON FOR INEFFECTIVENESS	NOT A REASON FOR INEFFECTIVENESS	NO RESPONSE[2]	TOTAL
1.	Message Delayed	9 (33%)	4 (15%)	14 (52%)	27 (100%)
2.	Media Edited the message	7 (26%)	6 (22%)	15 (52%)	27 (100%)
3.	Message overlapped with those from elsewhere	16 (60%)	2 (7%)	9 (33%)	27 (100%)
4.	Message given incorrectly	12 (44%)	4 (15%)	11 (41%)	27 (100%)
5.	Message given too infrequently	11 (41%)	4 (15%)	12 (44%)	27 (100)
6.	Our message made secondary to others	6 (23%)	4 (15%)	17 (62%)	27 (100)

1/ Additional ad-hoc answers included "official notices confused with interviews conducted with private citizens," "message given reflected media's own judgement," and "message was not heeded by the public."

2/ A variable number of responding jurisdictions answered each of the six items in this question. Jurisdictions which did not respond to a particular category are included under "NO RESPONSE." It is assumed these jurisdictions found media to be effective.



MAP 3
SOURCES OF EMERGENCY EQUIPMENT FROM LOCAL GOVERNMENTS FOR THREE STUDY JURSIDICTIONS (Yakima, Cheney, Ritzville)

For example, Yakima received equipment from both Seattle and Portland, partly because of its association with these larger cities in many statewide, professional and regional affairs. Ritzville and rural Adams County, which received both the greatest ashfall and the most national media attention, were inundated with high-priced offers of assistance from private sources. However, the most useful assistance came as the result of the ties between rural counties in Washington. On the fourth day after the eruption, a rural Kitsap County Commissioner called his counterpart on the Adams County Commission (a long-time friend) to ask if help was needed. The result was that several of the more rural coastal counties 300 miles away sent both equipment and public employees to beleaguered Ritzville.

State agencies ranked low as equipment sources, although several jurisdictions reported contacting them for assistance. This appeared due in part to simple resource scarcity. State government itself faced an awesome task in clearing hundreds of miles of highways. In one case, an Idaho community found itself competing for the same rental equipment as their district office of the Idaho Transportation Department. However, case studies revealed this was also due to lack of coordinative mechanism for allocating statewide aid. Where state agency assistance was gained, it was most often through direct contact with district or substate offices which local government works with daily rather than through centralized statewide coordination.

The frustration and adaptive learning experienced by local governments searching for equipment are well-illustrated by the case of the City of Cheney, only an hour's drive from Ritzville. In the words of Cheney's City Manager:

> We needed water trucks and we couldn't get them ... and Tuesday morning we started asking DES (state emergency agency) for water trucks, and we got nothing. Then we put out telexes to all points in the country to send us water trucks and we'd get responses back like "$100.00 AN HOUR F.O.B. PHOENIX," or "$125.00 AN HOUR F.O.B. REDDING, CALIFORNIA." We're not going to pay those rates!
>
> So we sat back and thought about it (as) we put our 10,000th call on the telex, and somebody called British Columbia. The way that evolved is we're trying to be logical about this. Nobody in Idaho is going to give up anything. I called one city manager who made me realize ... that that mountain was going to blow again and he wasn't going to let his equipment go. Nor was anybody over the west side (of Washington).
>
> Two days later I realized that help was not going to come from within the state. Every available water truck is going to be sucked up by (larger jurisdictions) able to pay those outrageous prices. the nearest people I know that I could "put the arm on" for a water truck are in the midwest because that's where all my professional acquaintances are. These are my thought processes ... I said, it's so simple ... British Columbia (Canada). Just go up there north of the border. We got a map of British Columbia and started calling the RCMP stations up there (to get phone numbers of local mayors, managers and city engineers). We made four phone calls ... Trail said, "we can only give the truck up for a week." Nelson said, "how can we get it down to you?" Fernie said "you bet."

Cheney's "foreign aid" resulted from on-the-spot adaptive learning, and the horizontal, situation-dependent relationships between communities instead of the top-down, vertical lines of assistance many jurisdictions initially tried to rely on.

COMMUNICATIONS AND THE MEDIA

Disaster researchers have argued that more attention needs to be paid to the role of the mass media in emergency planning and response (Wenger and others, 1980, p. 146). Again, the recovery from ashfall confirmed that belief, as radio stations played a major role. The case studies, however, revealed a host of operational problems and

questions of institutional behavior in implementing the response which deserve more attention. The overlapping message is a straightforward problem which ought to be anticipated in any multi-jurisdictional setting. But this hinges on how that setting is defined and who defines it. For example, the City of Spokane and Spokane County, encompassing 330,000 people, avoided conflicting messages due to an agreement established a year earlier to designate one spokesman for a joint council of city and county officials in any metropolitan emergency. But their messages overwhelmed and directly conflicted with specific instruction being given to residents of numerous outlying communities within a 100 mile radius!

Many of these smaller communities turned to adaptive communication strategies like the grapevine, to overcome the confusion caused by radio and T.V. overlap, but only after a rapid learning experience sometimes lasting several days. Even larger communities moved to establish special communication systems only after learning the limits of mass media and the emergency broadcast systems for giving detailed and changing local instructions. It is exactly these detailed instructions -- in this case on how to control the ash, organize public volunteer efforts and control auto use -- which social scientists have told us are essential to gaining effective cooperation from citizens (Perry and others, 1980).

The case studies also revealed some reasons why local radio and television stations were more effective than non-local ones. The accuracy of messages to citizens was much greater wherever jurisdictions were able to meet directly with media personnel on a daily basis, or arrange for regularly scheduled news briefings. This was most easily achieved in working with local stations. Large regional stations, particularly television, tended to treat official messages as news, and to edit it.

Countywide emergency plans simply did not anticipate these problems. The most common form of communications tool in these plans is a list of phone numbers for radio and T.V. stations, and these were frequently outdated. What was needed -- and developed -- was an ongoing process of understanding with media personnel that cannot be actualized by a list in a document.

ORGANIZING THE PUBLIC

The role of process was also brought out in case study information on how local government organized citizens to clean up the ash. We have probably all focused too much on evacuation as the primary citizen activity in emergencies. People are not always going to have somewhere to go. In this case they couldn't and they were needed to help overwhelmed public employees clean the ash. But local governments also faced the need to organize that effort, because citizens do not have their own supply of fire hose for washing down streets and heavy equipment for hauling it away.

More important, individual citizens are not used to working in teams under stress. As a practical matter, jurisdictions had to organize citizens to mitigate such problems as losing fire hydrants ruptured by persons inexperienced in their use and losing fire-fighting water supplies when everybody tried to clean their own property at once.

The experience with organizing citizens is probably the most thought-provoking one from the Mount St. Helens emergency. For conciseness, it can be illustrated by contrasting the experiences of two of the larger cities in eastern Washington as perceived by public officials. The first city, Yakima, organized a massive neighborhood cleanup program several days after the eruption, after a private effort sponsored by the chamber of commerce had its resources outstripped by the demand from neighborhoods. One administrator responsible for that effort was deeply impressed by what happened in certain neighborhoods:

> One of the areas I was really concerned about was the lower income areas because of the Block Grant (a federally funded neighborhood assistance program). What I found, and I physically went out and checked it, is that those lower-income people had their areas cleaned up quicker and were more organized than anybody else in the

community. ...it was interesting, the citizen participation approach that the people in the Block Grant areas took ... We've gone through that area (in the planning process) so that everybody knows everybody else on their block -- have their own little crime watch thing going and those kinds of things down in that area -- and they know each other.... The people who we'd been working with ... that's who we called and identified as their block leaders and coordinators (in the emergency).

An administrator in Moses Lake, which did not have a cleanup effort using citizen labor, echoed these same concerns from another point of view:

> You've got a problem of, really, organization and supervision there. There were a lot of questions like that. "Why don't you get into the neighborhoods and give 'em a coil of firehose and let them hook up to a hydrant." That sounds great when you talk about it, but it's going to take us days just to set up that sort of a plan, and we're busy doing other things. ... I would say that if we had time to set up that sort of plan and neighborhoods were already organized, that would be a great way to do it. But, on the other hand, I think it would take a long time to put something like that together, and that it would fall apart if you didn't use it. In other words, if we were able to set it up next week, and used it next week, that's great. If we set it up next week and never used it for a year's time, by that time it would be useless.

The implication here is that ongoing community development and problem-solving processes may be a tremendously important investment for effectively implementing emergency response when citizens must be active participants rather than passive bodies. Put another way, we can't expect to turn effective organization of citizens on and off like a light switch. The same observation may well apply to the experience with securing resources and communications after Mount St. Helens.

IMPLICATIONS FOR EMERGENCY PLANNING

There are many lessons here concerning specific operational techniques like maintaining contractor lists, standard rate agreements, extra phone jacks, and so on. But there are broader institutional implications about how we perceive planning needs in light of the actual problems of implementing a widespread emergency response.

First of all, the social scientists are right in telling us to be sensitive to behavior in planning emergency response measures. Clearly, local officials adopted many adaptive strategies reflecting this sensitivity on their own part and some of them were very similar to those suggested by researchers. However, they learned their way into these strategies in the heat of emergency. The question facing us then is how to promote creative, situation-dependent strategizing before a hazard strikes. One method of internalizing the lessons of this and other emergencies may be to focus more on local learning and capacity-building which is sensitive to each area's setting, institutions and practices. One approach being taken to this is through the development of simulation games for developing actual emergency plans with, not for, the actors who will have to use them. Such an approach has been developed by the Academy for Contemporary Problems for FEMA and is now being field-tested in the Atlanta federal region. It is the opposite of the top-down approach taken in the civil defense preparedness system.

But the Mount St. Helens recovery also implies that social scientists and public administrators need to give more attention to the institutional context in which the response is implemented. There is a somewhat flawed assumption about the role of the civil defense oriented countywide emergency coordination system in operations which require large amounts of material, public works expertise and citizen involvement. This role clearly fell to general purpose local government after Mount St. Helens. There is a definite need

to bring the operational officials of local government more closely into defining the scope and objectives of emergency planning.

But beyond this, the observations in this study tentatively suggest that current intergovernmental funding of preparedness planning is creating a two-tiered system of plans. The first tier are the federally mandated nuclear response plans embodied in the countywide coordination model. The second tier consists of local procedures which develop out of the context of each jurisdiction's experience, potentials, and constraints. The chilling implications of this situation are suggested by the attitude of one city manager in the ashfall zone towards the massive urban to rural evacuation plans currently being institutionalized through the county coordination system. He said, "The civil defense training a year ago was useful organizationally, but it'll never work operationally."

What's our alternative to this approach? We need to look beyond what we think should work for local officials in emergency to what they think will work for them, in their settings. Social-psychologist Donald Michael suggests that we need "to use crises for discovering new options ... in post-disaster periods (Michael 1974). He argues that we need to develop organizations that are open to the new and unexpected instead of the "familiar and reliable" -- or what he calls "organizations that can adaptively learn how to plan." The practical experience with Mount St. Helens supports this argument well.

LITERATURE CITED

Friedmann, J., 1979, Innovation, flexible response and social learning: a problem in the theory of meta-planning, in Burchell, R.W., and Sternlieb, G., editors, Planning theory in the 1980s: a search for future directions.

Friedmann, J., 1973, Retracking America: a theory of transactive planning: Anchor Press, Garden City, New York.

Griffin, C.T., and Griffen, B.S., 1975, System stress and the persistence of emergent organizations: A Comment: Sociological Inquiry, v. 45, p. 71.

Holgate, J., 1978, Personal communication to R.W. Perry, cited in Perry, 1979, Incentives for evacuation in natural disaster: JAPA, v. 45, p. 4.

Michael, D.N., 1973, On Learning to plan -- and planning to learn: Jossey-Bass, San Francisco.

Michael, D.N., 1974, Speculations on future planning process theory, in Godschalk, David R., editor, Planning in America: learning from turbulence: American Intitute of Planners, Washington, D.C.

Miletti, D.A., Perry, R.W., and Gillespi, D.F., 1975, The Analytic use of case study materials: A Rejoinder to Griffin and Griffin: Sociological Inquiry, v. 45, p. 72 and 50.

Perry, R.W., 1979, Incentives for evacuation in natural disaster: Journal of American Planning Association, v. 45, p. 440-447.

Perry, R.W., Lindell, M.K., and Greene, M.R., 1980, Evacuation decision-making and emergency planning: Battelle Memorial Institute, Seattle, NSF Grant No. PFR-77-23697.

Susskind, L.E., 1974, The Future of the planning profession, in Godschalk, David R., editor, Planning in America: Learning from Turbulence: American Institute of Planners, Washington, D.C.

Wenger, D.E., Faupel, C.E., and James, T.F., 1980, Disaster beliefs and emergency planning: University of Delaware, NSF-RANN Grant No. ENV77-10202.

U.S. GEOLOGICAL SURVEY ROLE AT MOUNT ST. HELENS BEFORE AND DURING EARLY 1980-GEOLOGIC STUDIES AND COORDINATION WITH PUBLIC AGENCIES

Donal R. Mullineaux
U.S. Geological Survey
Denver Federal Center, Denver, Colorado

ABSTRACT

U.S. Geological Survey (USGS) studies of Mount St. Helens between about 1955 and 1980 included topical studies of mudflow and ash deposits, stratigraphic and mapping studies, seismic investigations, and, starting in 1970, a comprehensive study of the volcano to evaluate its eruptive history and volcanic hazards. Several of these studies were carried on in cooperation with university scientists. Reports published in 1975 and 1978 identified Mount St. Helens as the most active and most explosive Cascade volcano during the last few thousand years, and predicted explosive eruptions in the future. When the activity began in 1980, a seismic-monitoring network had already been installed and a volcanic-hazards appraisal had been published.

Coordination with public agencies prior to 1980 consisted chiefly of informal cooperation; however, a formal "Notification of Potential Hazard" for Mount St. Helens had been released by the USGS in 1978. Beginning in March 1980, government agencies were provided with monitoring data and interpretations, and appraisals of potential eruptions and hazards. This information was also given to private companies, other concerned groups, news media representatives, and the public. Hazards appraisals included descriptions of kinds, scales, characteristics, extents, relative probabilities, effects and possible mitigation of expectable events, and were based on current monitoring data as well as the record of past eruptions of Mount St. Helens.

Hazards appraisals were used for making decisions regarding such problems as need for evacuation, access restrictions, precautions for working near the volcano, and contingency planning. Much of that information, however, especially forecasts of events and hazards, could be stated only in probabilistic form; thus, public officials and others had to make decisions based on probabilities rather than certain predictions.

GEOLOGIC STUDIES

Recent geologic studies by the U.S. Geological Survey (USGS) of Mount St. Helens started in the late 1950s when D.R. Crandell and D.R. Mullineaux investigated mudflows in the Toutle River Valley (Mullineaux and Crandell, 1962). The mudflows had formed Silver Lake, 50 km west-northwest of the volcano, by damming a small valley tributary to the Toutle. As a result of that mudflow investigation, we also began work on the age of Mount St. Helens (Mullineaux and Crandell, 1960). In the early 1960s, R.D. Miller of the USGS and Mullineaux traced some volcanic ash deposits from Mount Rainier National Park to Mount St. Helens, and Mullineaux began to study these and other ash deposits from Mount St. Helens (Mullineaux, 1964). It should be noted that both these investigations started with study of eruptive products that were far from the source volcano. In the late 1960s, J.H. Hyde, now at Tacoma Community College, began a stratigraphic study of volcanic deposits southwest of Mount St. Helens (Hyde, 1975), and C.A. Hopson of the

University of California at Santa Barbara began to make a geological map of the volcano and to study the volcano as a petrochemical system in an attempt to understand the sequence of eruptions (Hopson, 1971).

In 1970, Crandell and Mullineaux started a comprehensive study of all the volcanic products in order to determine the eruptive history of Mount St. Helens and to assess potential volcanic hazards from future eruptions (Crandell and Mullineaux, 1978). Also in the 1970s, a University of Washington-USGS seismic research group at Seattle investigated seismic activity at Mount St. Helens, and before 1980 had installed seismometers at and near Mount St. Helens (Endo and others, 1981; Malone and others, 1981).

Our volcanic hazards study attempted to determine the kind, frequency, scale, and extent of past eruptions and their effects, from which we could infer potential volcanic hazards. These studies emphasized but were not limited to fragmental deposits; our work at other volcanoes had convinced us that fragmental deposits reveal an especially detailed record of past activity, and also may be the only records of some of the most dangerous kinds of volcanic events. Many relatively dangerous eruptions produce only fragmental deposits; pyroclastic flows and lateral blasts, for example, are particularly dangerous kinds of events.

We conducted much of our study in areas adjacent to the volcano rather than on the mountain itself, where the products of recent eruptions tend to bury and hide the record of older activity. We also traced deposits downvalley and downwind from the volcano, in order to determine what areas had been affected by various kinds and scales of events, and how frequently.

We published reports of past activity and volcanic hazards in 1975 and 1978 (Crandell and others, 1975; Crandell and Mullineaux, 1978); the reports described the past eruptive record of Mount St. Helens and potential hazards from future eruptions. These reports identified Mount St. Helens as the most active of the major Cascade Range volcanoes, and probably the dangerous. These reports also outlined potential hazard zones, and described characteristics and past frequency of various hazards.

So, when the 1980 activity began, a report of potential hazards from the volcano had been published, a seismic surveillance system that could detect volcanic earthquakes under Mount St. Helens was in operation, and the USGS had issued a formal "Notification of Potential Hazard" for Mount St. Helens. Scientists and governmental agencies were better prepared in 1980 for volcanic activity at Mount St. Helens than they would have been for such activity at any other volcano in the Cascades.

COORDINATION AND INFORMATION PROVIDED

Our coordination with public agencies prior to 1980 consisted of formal and informal cooperation and provision of published and unpublished data to other agencies. Considerably increased coordination with other agencies began shortly after March 20 in response to the activity at Mount St. Helens. The University of Washington-USGS group in Seattle immediately provided seismic data (Endo and others, 1981), and the volcanic hazards group in Denver contributed information on potential hazards, mostly by telephone (Miller and others, 1981). Both groups discussed the possibility of an eruption. As frequency and magnitude of the earthquakes increased, the Seattle group expanded the seismic network around the volcano, determined the earthquakes to have originated beneath the volcano, and provided frequent updates of seismic data to federal and state agencies. After March 25, volcanic hazards appraisals were updated in Vancouver as USGS people moved there from Denver and other USGS centers. Logistical support and cooperation of the U.S. Forest Service (USFS) in Vancouver was essential to the USGS activities. The USFS was well organized for and experienced in handling emergencies in the area, and controlled much of the threatened land. Almost everything required for USGS operations, including logistical support and office space, was initially provided by the USFS.

During the initial phases of activity at Mount St. Helens, information on volcanic hazards was based entirely on interpretation of past eruptive events at the volcano. Those events had included a wide variety of activity, such as eruptions of airfall volcanic ash, a lateral blast, pyroclastic flows, hot and cold mudflows, lava flows, domes, and floods (Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981). The products of past volcanic activity also indicated a wide range of scale or volume of eruptions, and the numbers of different events indicated that small eruptions were more likely at Mount St. Helens than large ones.

Verbal descriptions of past eruptive events and distribution of their products, however, were not adequate for the needs of local officials. Consequently, Crandell prepared a large-scale map of potential hazards on a USFS base map with which most local officials were familiar. The map illustrated possible distributions of airfall tephra of various thicknesses, and of pyroclastic flows and mudflows for eruptive events of three different magnitudes: (1) those comparable to the largest known at Mount St. Helens from the geologic records; (2) those comparable to small, relatively frequent events such as those that occurred repeatedly during the middle of the 19th century; and (3) events of an intermediate size. We were not able to say, however, which of these would actually occur. Events larger than those recognized at Mount St. Helens, such as the eruption of Mount Mazama at the site of Crater Lake about 7,000 years ago, were discussed at various times. We considered the probability of such an eruption to be so low, however, that extents of hazard zones for events of that magnitude were not shown on the map, nor did we suggest that a similar event was likely to occur at Mount St. Helens.

As eruptive activity continued into April and the bulge on the north side of the volcano expanded. The north flank of the volcano and areas downslope and downvalley were recognized and described as areas most likely to be affected by further volcanic activity.

Government officials and other people needed to know potential locations, characteristics, and effects of various kinds of eruptions in order to consider appropriate mitigation measures. Consequently, we emphasized factors such as the influence of wind direction and topography on areas that would be affected by airfall tephra, pyroclastic flows, mudflows, and floods. The relative probability of these events and their potential severity were evaluated in regard to a possible need for excavation of some areas, and with respect to such factors as potential dangers along various escape routes and appropriate kinds of protection for persons who would be in areas threatened by eruptions. We drew hazard zones around the volcano, but did not make decisions regarding closure zones on their boundaries.

We disseminated this information chiefly to public agencies, first by telephone and then through many meetings at the Emergency Coordination Center (ECC) at the USFS headquarters in Vancouver, and at other conferences. Agencies involved included Federal agencies such as the USFS; state agencies such as the Department of Emergency Services, Washington State Patrol, and Department of Transportation; county officials including sheriffs and commissioners; and some city officials. In addition, representatives of various private companies responsible for or working on land around the volcano attended many meetings. We also passed information through individual contact on many occasions. The information we distributed to agency officials was also discussed at many public meetings, at press conferences coordinated by USFS, and during the course of interviews with individuals.

The establishment of an ECC by the USFS was especially important, and was essential to the dissemination of information. Representatives of other agencies, companies, and other concerned groups could gather there, and some were represented around the clock. Information was integrated at the ECC from the USGS monitoring and observation activities and also from other agencies and persons, and was evaluated for the use of people making deicisions concerning response to potential hazards.

EFFECTIVENESS OF HAZARDS ASSESSMENTS

Many of our predictions of effects and extents of volcanic phenomena were accurate,

and the information was used effectively by authorities responsible for operations near the volcano. The magnitude of the laterally directed blast on May 18, however, was unprecedented at Mount St. Helens and was unanticipated. We had considered the possibility of blasts on a smaller scale, but their effects would not have extended beyond the hazard zones drawn for the more expectable pyroclastic flows and mudflows. We had also considered larger directed blasts such as had occurred at some other volcanoes, but their extents had not been drawn on hazards maps because we did not regard them as likely to result from eruptions at Mount St. Helens. Effects of other events generally were adequately anticipated -- the extents of the mudflows in the Toutle River-Cowlitz River system, for example, were similar to those shown on the published hazard map (Crandell and Mullineaux, 1978, Plate 2). On the south side of the volcano, Swift Reservoir had been drawn down in anticipation of possible mudflows, and Swift Dam was not overtopped or damaged when mudflows entered the reservoir on May 18. Almost all people had been evacuated from the upper valley of the North Fork Toutle River, and access to that area had been restricted. Normally, 1,000 to 3,000 people would have been in the Spirit Lake recreation area on a weekend at that time of year; interest in the volcanic activity would undoubtedly have increased that number in 1980. Decisions by authorities to close that area and to resist strong public pressure to reopen it held the death toll on May 18 to a small fraction of what it otherwise could have been.

We found that two concepts were especially difficult to explain to some authorities and to the public at large: the limitations of the predictions we could make, and the meaning of the hazard-zone boundaries. We were often asked for exact forecasts of the time, kind, scale, or extent of eruptions. We did not think, however, that specific predictions of that kind could be reliable enough to be helpful. In some cases, an estimate of the chances that a certain eruptive event will occur can be made, or a statement that one kind or magnitude of event is more or less likely than another. Our probabilistic predictions were regarded as inadequate by some people, and probably gave rise to a phrase that appeared in news-media reports that "those geologists are harder to corner than a rate in a roundhouse." Nevertheless, people who will have to use scientific appraisals of hazards in the future will likely have to make use of similar probabilistic statements.

A second source of difficulty for many people was the meaning of hazard-zone boundaries on maps. Most boundary lines for such zones are rather arbitarily placed, and simply connect points at which the degree of hazard is expected to be about equal. Or, in terms of a gradationally decreasing danger outward along a line from the volcano, the boundary represents one point along that gradual decrease. Except for certain types of hazards or topographic conditions, there is not a significant difference in hazard from immediately on one side of the boundary line to just on the other side. A line drawn on a map along a topographic scarp tens or hundreds of feet high can separate important differences in risk from lava flows, but lines drawn to show decreases in risk outward from a Cascade Range volcano for a pryoclastic flow, for example, do not.

CONCLUSION

The experience at Mount St. Helens in 1980 suggests that several procedures might be improved in making hazards appraisals and responding to eruptions in the future, especially: (1) quantify predictions as much as possible even though they are probabilistic; (2) increase public understanding of the use of probability in predictions; (3) stress the possibility and danger of infrequent but catastrophic events, even though the probability of their occurrence may be extremely low; (4) emphasize more that some events can occur with little or no warning; and (5) explain more effectively the meaning of hazard-zone boundaries.

REFERENCES

Crandell, D.R., Mullineaux, D.R., and Rubin, Meyer, 1975, Mount St. Helens volcano; recent and future behavior: Science, v. 187, p. 438-441.

Crandell, D.R., Mullineaux, D.R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

Endo, E.T., Malone, S.D., Noson, L.L., and Weaver, C.S., 1981, Locations, magnitudes, and statistics of the March 20-May 18 earthquake sequence, in Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 93-108.

Hopson, C.A., 1971, Eruptive sequence at Mount St. Helens, Washington (abstract): Geological Society of America Abstracts with Programs, v. 3, no. 2, p. 139.

Hyde, J.H., 1975, Upper Pleistocene pyroclastic-flow deposits and lahars south of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-B, 20 p.

Malone, S.D., Endo, E.T., Weaver, C.S., and Ramey, J.W., 1981, Seismic monitoring for eruption predictions, in Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 803-814.

Miller, C.D., Mullineaux, D.R., and Crandell, D.R., 1981, Hazards assessments at Mount St. Helens, in Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 789-802.

Mullineaux, D.R., 1964, Extensive recent pumice lapilli and ash layers from Mount St. Helens volcano, southern Washington (abstract): Geological Society of America Special Paper 76, p. 285.

Mullineaux, D.R., and Crandell, D.R., 1960, Late recent age of Mount St. Helens volcano, Washington: U.S. Geological Survey Professional Paper 400-B, p. 307-308.

Mullineaux, D.R., and Crandell, D.R., 1962, Recent lahars from Mount St. Helens, Washington: Geological Society of America Bulletin, v. 73, p. 855-870.

Mullineaux, D.R., and Crandell, D.R., 1981, The eruptive history of Mount St. Helens, in Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 3-15.

OPERATIONS OF THE U.S. GEOLOGICAL SURVEY AT MOUNT ST. HELENS

Donald W. Peterson, Scientist-in-Charge
Mount St. Helens Project
U.S. Geological Survey

SUMMARY OF OPERATIONS

Work by the U.S. Geological Survey at Mount at Helens can be grouped in four major categories:

1. Monitoring the volcano -- observation, measurement, and analysis of the current, ongoing state of the volcano. Systematic monitoring includes visual and photographic observations, measurements of seismicity in cooperation with University of Washington, ground deformation, gas emission rates, and magnetic field. Additional studies done occasionally include gravity, electromagnetic, geoelectric, and temperature measurements.

2. Studies of volcanic products and processes -- the materials emitted by the volcano and processes by which they were generated, erupted, transported, and emplaced. These include the debris avalanche deposit, mudflows, blast deposit, air-fall tephra, pyroclastic flows, lava domes, and volcanic gases.

3. Hydrologic monitoring and studies of hydrologic products and processes -- the effects of volcanic events on the rivers, lakes, floodplains, glaciers, and snowpack, and the effects of rain and running water on the volcanic deposits. Examples include measuring water and sediment discharge, repeated surveys of channel cross sections, determining hydrologic properties of new deposits, investigating processes of mudflow and normal stream-sediment transport, and determining the chemical and biological quality of water.

4. Prediction and hazard assessment. The ultimate aim of all these activities is to gain a better understanding of the natural processes operating at Mount St. Helens and vicinity. By correlating ongoing observations with past events and the basic processes, a capability to predict volcanic and hydrologic events can be developed, and the hazards offered by the volcano can be evaluated in terms of changing conditions. Continuing improvement in the precision of predictions for the volcanic eruptions has been achieved. General assessments of the hazards are periodically updated and provided to concerned agencies and to the public.

These operations have covered the volcanic activity and associated phenomena that began at Mount St. Helens in March 1980. The nature of the volcanic activity is summarized in Figure 1.

EARLY ORGANIZATION OF THE SCIENTIFIC EFFORT

A confusing set of demands confronted scientists when they first arrived at Vancouver, Washington, following the onset of volcanic activity at Mount St. Helens in late March of 1980. These included a combination of scientific and other needs -- the need to monitor, observe, and interpret the volcanic events, to coordinate operations and

exchange information with other agencies, to satisfy the needs of the public for reliable information, and the need to organize and coordinate the activities of many scientists at a spot where no USGS office or structured organization existed. The situation is summarized by Figure 2. A close coordination with and dependency on the U.S. Forest Service quickly developed, who provided office space and logistical support. The complexities of the early weeks were further compounded with the cataclysmic eruption of May 18. In spite of the difficulties, the major requirements were effectively met through the gradual evolution of a loosely-structured organization that by early June appeared something like Figure 3. Each of the tasks illustrated were accomplished by a continually rotating staff, as instant transfers to Mount St. Helens could not be carried out, and all participants had ongoing responsibilities elsewhere. It was realized early, however, that Mount St. Helens would require a long-term commitment by a resident staff, and office and laboratory space had to be acquired. Even though the Forest Service was very hospitable throughout, it was not feasible to continue to occupy their facilities. Through the summer of 1980 members of the resident staff were recruited, a field office was officially established, temporary quarters were acquired, and through the succeeding months scientists and technicians were gradually transferred to Vancouver. By early 1981 virtually all the tasks were being carried out by the resident staff.

Both the Geologic Division and the Water Resources Division of the Geological Survey are involved in the studies of Mount St. Helens. A closely integrated operation has been developed, as some of the scientific responsibilities are overlapping and close cooperation enhances effectiveness. In addition, administrative support, aircraft logistics, and office facilities and equipment are shared.

MONITORING

Monitoring activities include those studies that provide observations and records of the current, ongoing state of the volcano at any particular time. Several different kinds of geologic, geophysical, and geochemical monitoring are carried on at Mount St. Helens.

One of the most important is simple visual observation, systematically recorded and photographed. The character of volcanic events themselves, as well as the morphologic changes that result from the activity, are best documented through observation and photography. Every staff member going in the field contributes to this effort.

Seismic studies are carried on as a joint operation of the Geophysics Program of the University of Washington and the Geological Survey. Roughly 16 seismic stations within about 40 km of the volcano provide records pertinent to the volcanism at the mountain (Figure 4). Signals are telemetered to the Geophysics Laboratory at the University in Seattle where they are recorded, processed, and interpreted. Helicorders in Vancouver provide visual records of three selected stations, and frequent telephone conversations between Vancouver and Seattle provide necessary information exchange regarding seismic and volcanic conditions.

Studies of ground deformation are carried out by several different methods. Lateral distances between established points are measured at regular intervals by an electronic distance-measuring (EDM) instrument that utilizes a laser beam to determine the distance (Figure 5). Prior to eruptions, points near the vent move outward at ever-accelerating rates, and the technique (Figure 6) has become an essential tool in monitoring the state of the volcano. Prior to high-volume explosive eruptions, such as those during 1980, points on the outer flank of the volcano moved, whereas prior to the quiet lava extrusions that added to the composite dome during 1981, only those points moved that are near the dome in the inner crater.

Another important means of detecting ground deformation is by measuring changes in the slope of the ground surface using both tiltmeters and high precision optical

DATE	TYPE OF ACTIVITY						
	Steam and Ash	Land-slide	Lateral Blast	Airfall Tephra	Pyro-clastic Flow	Mud-flow	Lava Dome
1980							
Mar 27 - Apr 22	X	-	-	-	-	-	-
May 7-14	X	-	-	-	-	-	-
May 18	X	X	X	X	X	X	-
May 25	-	-	-	X	X	-	-
Jun 12	-	-	-	X	X	X	-
Jun 13-19(?)	-	-	-	-	-	-	X
Jul 22	-	-	-	X	X	X	-
Aug 7	-	-	-	X	X	-	-
Aug 8-10	-	-	-	-	-	-	X
Oct 16-18	-	-	-	X	X	-	-
Oct 18-19	-	-	-	-	-	-	X
Dec 27-Jan 3	-	-	-	-	-	-	X
1981							
Feb 5-7	-	-	-	-	-	-	X
Apr 10-12	-	-	-	-	-	-	X
Jun 18-20	-	-	-	-	-	-	X
Sep 6-11	-	-	-	-	-	-	X
Oct 30-Nov 2	-	-	-	-	-	-	X

Figure 1. Survey of dates and type of activity in eruptions of Mount St. Helens, 1980 and 1981.

Figure 2. Illustration of the multiple matters requiring the attention of scientists during the initial activity at Mount St. Helens.

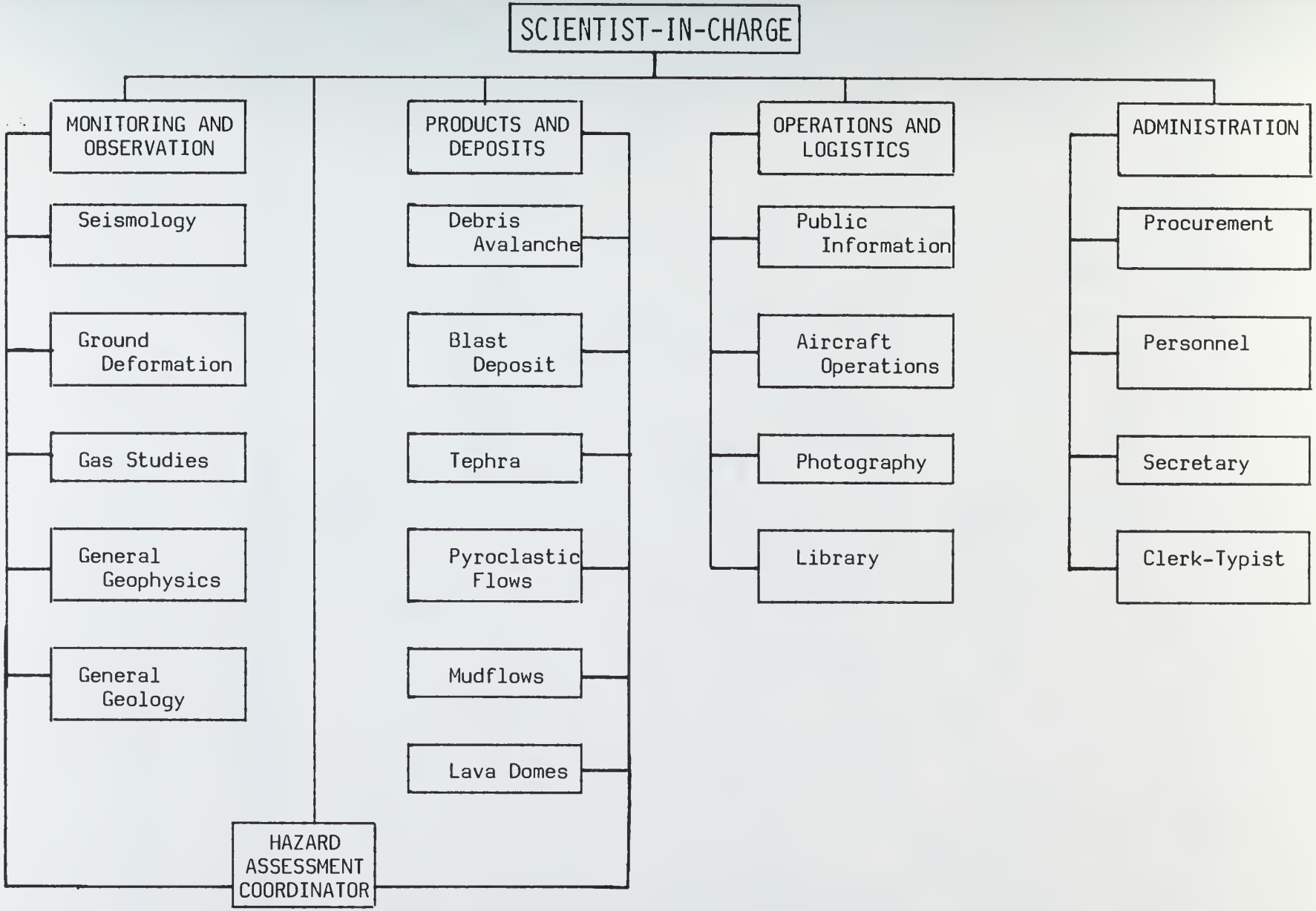


Fig. 3. Organization chart of functions performed by Mount St. Helens Project as developed by late 1980.

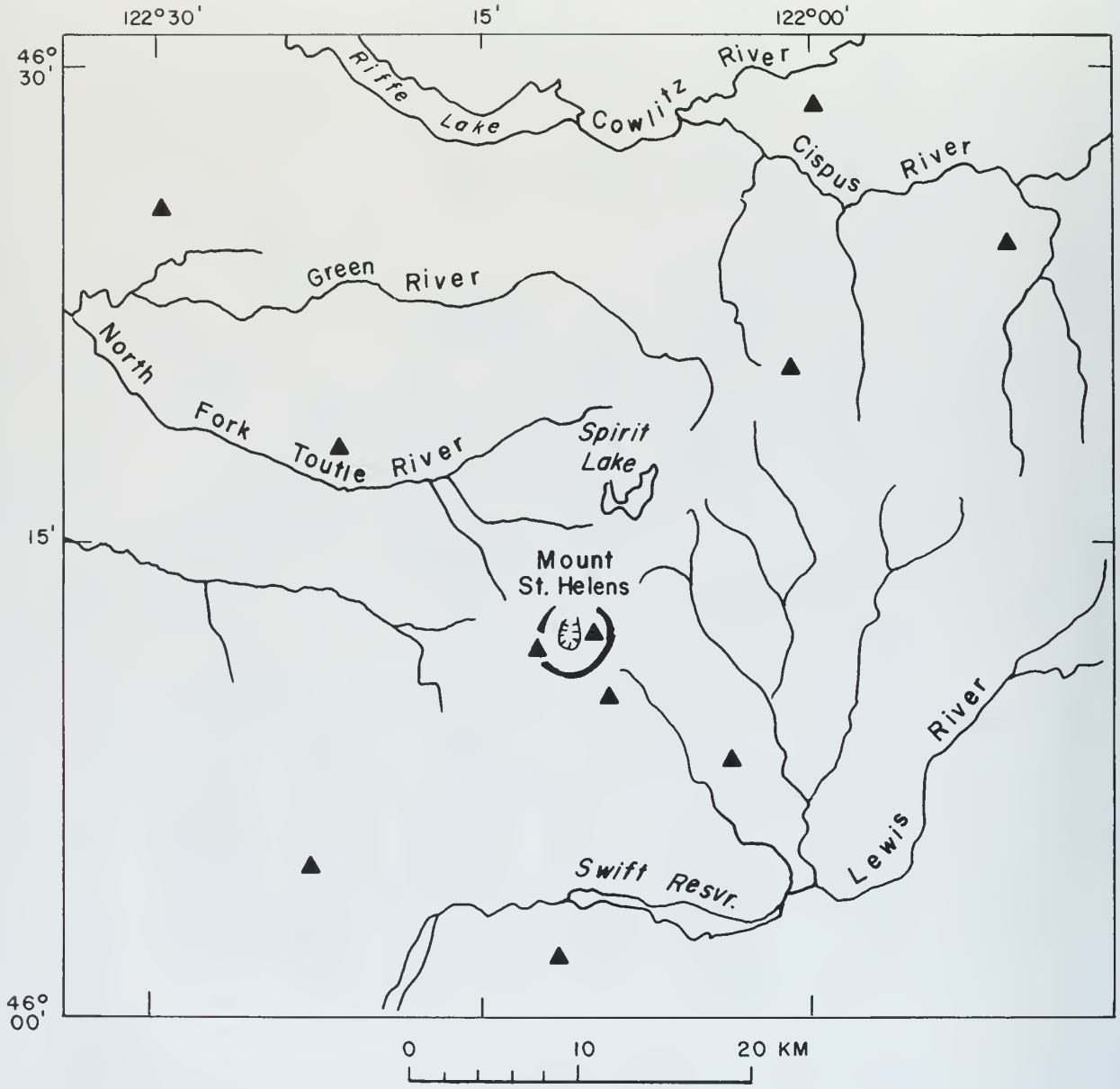


Figure 4. Location of seismic stations in the vicinity of Mount St. Helens. Several stations beyond the map boundary are also useful for interpreting seismicity at the volcano.

Figure 5. Example of the network of points monitored by EDM methods during the summer of 1980. Triangles are instrument stations; circles are reflector stations (from Figure 92, USGS Prof. Paper 1250).

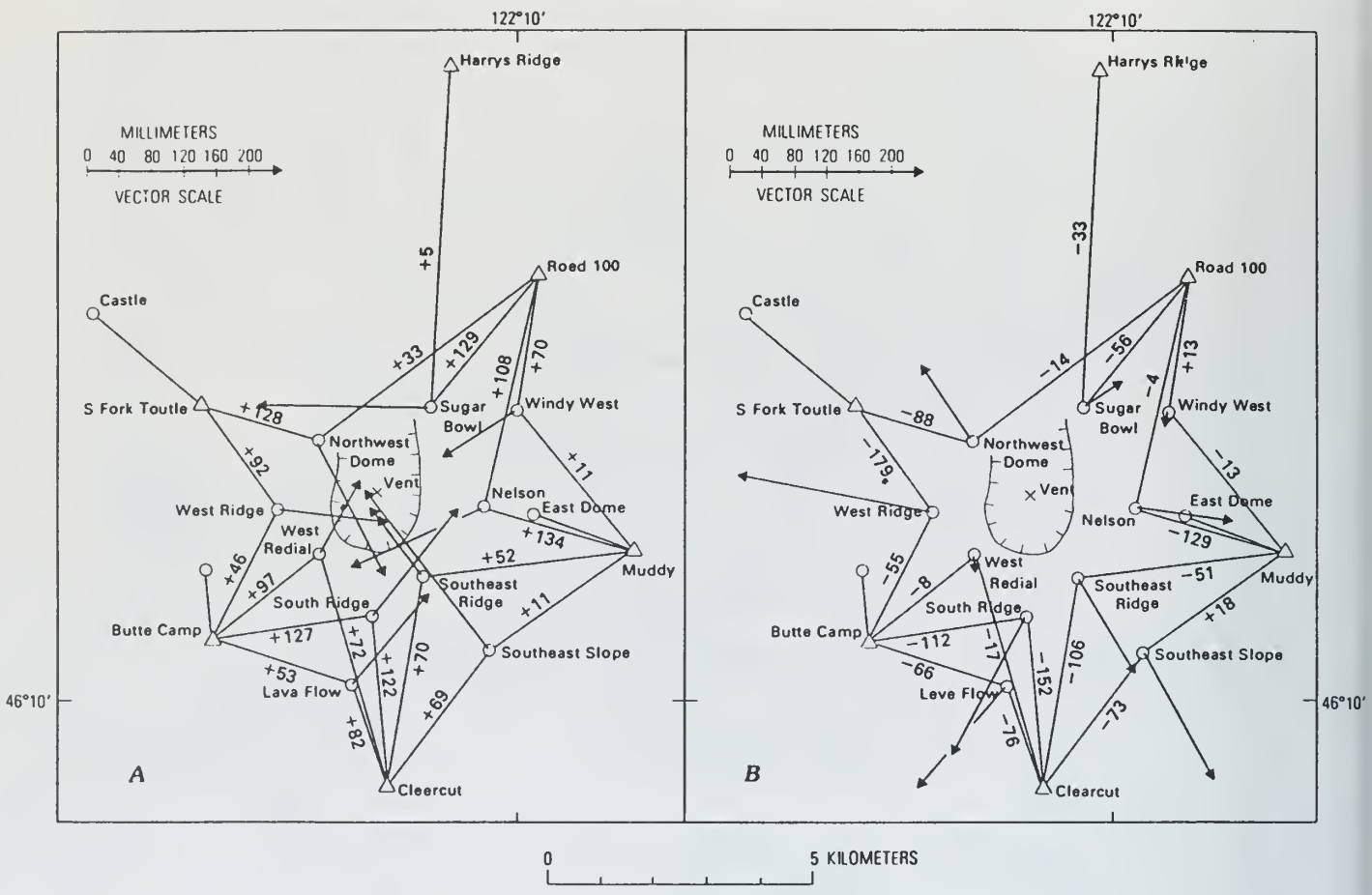


Figure 6. Illustrations of changes (in millimeters) of slope distances during periods of contraction and expansion (from Figure 98, USGS Prof. Paper 1250).

surveying instruments. Surveyed level-lines are also periodically reoccupied. These methods indicate vertical changes of the ground, whereas the EDM technique primarily detects horizontal changes. The network includes a few electronic tiltmeters for which the signal is telemetered back to Vancouver, providing remote monitoring capabilities for ground deformation. A theodolite is used to monitor vertical angle changes between established points; this is particularly useful for detecting movement of points on the lava dome.

During 1981, a number of thrust faults were discovered on the crater floor adjacent to the dome. Careful observation revealed that these faults were particularly active during the periods just prior to eruptions. A network of points along these thrust faults were periodically measured with a surveyor's tape, and accelerating rates of movement proved to be a powerful tool for predicting eruptions. These various techniques are most useful when compared with one another and when used in conjunction with seismicity and gas-emission data. The combination of techniques has enabled every eruption in 1981 to be successfully predicted, and public forecasts were issued prior to the eruptions of April, June, September, and October.

Emission rates of SO^2 gas from crater fumaroles are measured regularly using an aircraft-mounted correlation spectrometer (COSPEC). The airplane is flown beneath the gas plume repeatedly for the instrumental observation, and calculations involving the speed and direction of both the aircraft and the wind yield a value for the emission rate of SO_2 in tons per day. Rates have varied in a complex way, but prior to some (not all) eruptions, the emission rates increase.

From mid to late 1980, emission rates of CO_2 gas were determined using an aircraft-mounted infrared spectrophotometer. In this technique the aircraft is flown through the plume and CO_2 is physically collected and concentration measured. Again, calculations involving speed and direction of aircraft and wind yield emission rates in tons per day. Prior to the eruptions of July 22, August 7, and October 16-18, 1980, the emission rate of CO_2 declined progressively for a few days. This absolute decline, along with an associated decline in the ratio CO_2:SO_2, showed promise as a prediction tool. However, a few other periods when the ratio declined were not followed by eruptions, neither were they associated with seismic or ground deformation precursors. In late 1980, and throughout 1981, emission rates of CO_2 had fallen to levels below detectability by the instrument, precluding further testing of the applicability of the technique. However, even without CO_2, the emissions rates of SO_2 continue to be studied to learn more of its behavior associated with eruptions.

In addition to aircraft monitoring of gas, occasional gas collections are made at fumaroles in the crater. Gas species identified by various investigators include H_2O, CO_2, SO_2, H_2S, H_2, CO, HCl, HF, COS, CS_2, and CH_4. Fumarole temperatures are also measured on an occasional basis. Temperatures have sometimes risen at some fumaroles prior to eruptions, wherein other vents show no change.

The magnetic field is monitored at two stations on the volcano, and measurements are telemetered to the observatory at regular intervals. Changes in the magnetic field have been associated with some eruptions, but the relations are complex and more study is needed before the technique can assume a role among the regular monitoring tools.

Other kinds of studies performed at irregular intervals include gravity, electromagnetic, resistivity and other geoelectric techniques, and airborne infrared scanning, some of these methods in cooperation with investigators outside the Geological Survey. These studies help understand and place constraints on the concepts developed of the internal workings of the volcano, but they are not among the tools that can yet be used for predicting impending activity.

VOLCANIC PRODUCTS AND PROCESSES

The studies described above are concerned with the current, ongoing state of the volcano, that is, the present tense. Other studies are concerned with what the volcano has already done, that is, the past tense. These investigations are devoted to studying the different kinds of products that have been emitted by the volcano and at interpreting the processes involved in their eruption, transport, and deposition.

On May 18, 1980, the products included a tremendous landslide and debris avalanche, blast deposit, pyroclastic flows, airfall tephra, and mudflows. Subsequent eruptions, much smaller in volume and energy release, have included airfall tephra, pyroclastic flows, mudflows, and lava extruded to develop a composite lava dome.

Because the May 18 and subsequent eruptions have been observed, with varying degrees of detail and adequacy, the volcanic products provide rich opportunities to relate the characteristics of the deposits to the processes by which they formed. New insights can then be gained on processes involved in the emplacement of old volcanic rocks and at other less-well observed volcanoes in other parts of the world.

HYDROLOGIC PROCESSES

The eruption of May 18 caused profound changes to the hydrologic system on and around the volcano. The Water Resources Division of the Geological Survey has mounted an intensive effort to study the effect of eruptions on the streams, lakes, glaciers, and groundwater. This presentation gives but brief mention to these studies. However, more than half of the USGS personnel stationed at Vancouver are members of the Water Resources Division involved in these studies.

It is convenient to regard the studies in two major categories: (1) studies concerned with the effect of eruptions and volcanic products on the hydrologic regime; and (2) studies concerned with the effects of rain, snow, and runoff on the deposits, the landscape, and the surrounding region.

The drastically changed landscape and the unstable new deposits pose a long-term concern for possible future floods and mudflows. These might be associated with future eruptive activity, or they might occur totally unrelated to the volcano, induced simply by storms or ongoing hydrologic processes. The conditions require a long-term commitment of careful attention.

PREDICTION AND HAZARD ASSESSMENT

Monitoring and the study of volcanic products are of great scientific interest and value, but their ultimate practical value to society as a whole is their utility in predicting eruptions and in assessing the hazards posed by the volcano. The most common questions about the volcano are "When is it going to erupt again?" and "How long are we likely to have eruptions?"

To attempt to answer these critically important questions is the ultimate justification for the program of research at any volcano. All of the above studies are utilized in this effort. Results of observations and monitoring are incorporated with the actual behavior and the volcanic products to gain a better understanding of the fundamental internal processes of the volcano. Figure 7 illustrates diagrammatically how the various activities are coordinated to understanding processes and ultimately to predictions and hazard assessments. Progress is being made, but obviously much more is needed, and the science of volcanology is still in its infancy.

It is convenient to regard prediction and hazard assessments as falling into three, broad, time frames -- short, intermediate, and long. The short term covers the outlook over a period of hours or days, and predictions attempt to be specific as to time. In addition, short-term assessments are useful and economically valuable in assuring the public when no eruption is anticipated. The intermediate term covers the outlook over periods of, say, a week to perhaps a few months. The timing of any impending event is vague and can't be expected during the intermediate term. The long term is applied to the span of years, decades, and

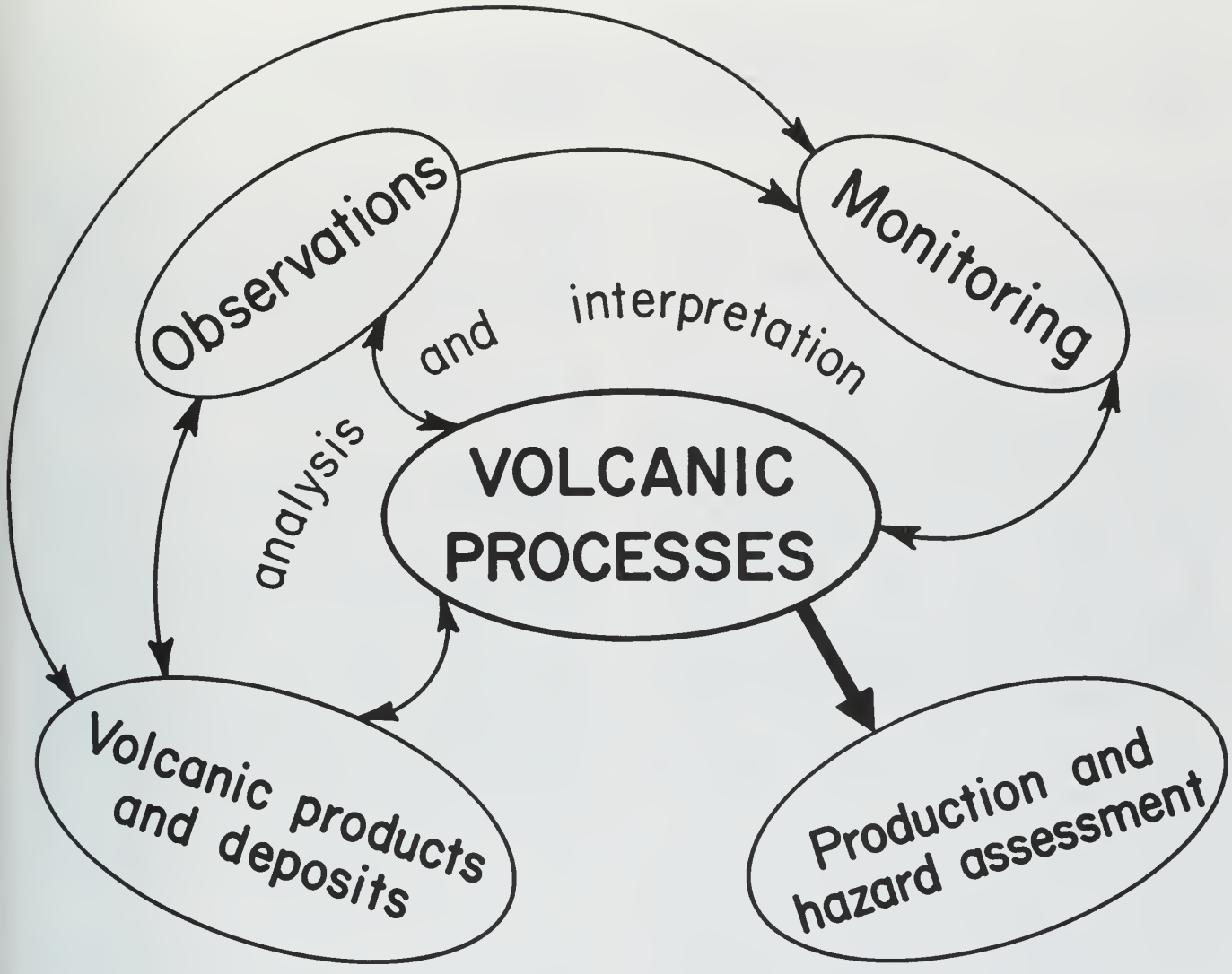


Figure 7. Diagrammatic illustration of interrelations among different kinds of studies, which lead to understanding of processes, which in turn are necessary for prediction and hazard assessment.

centuries. The long term does not apply to specific eruptions, and is not applicable to predictions, but it is highly pertinent to the broad range of expectable types of activity, their severity, frequency, and areas affected. They are applicable when considering the general problems of land-use planning.

Further information on all the foregoing studies is provided in recently published U.S. Geological Survey Professional Paper 1250, edited by P.W. Lipman and D.R. Mullineaux (1981).

DISCUSSION

Question: What are the quantities of the gases being emitted?

Peterson: In the summer of 1980, the sulfur dioxide emission rates were generally between 1,000 and 1,500 tons per day. The maximum recorded rate was 3,400 tons per day. This has progressively fallen off, and in late 1981 was generally around 100 or 200 tons per day. The rate of carbon dioxide was commonly about five times higher; during the summer and fall of 1980 it averaged from 5,000 to 11,000 tons per day, and had a maximum of 22,000 tons per day. CO_2 emission rates are now below determination by the methods used, but if the CO_2:SO_2 ratio has remained similar, it may be inferred that they are around 500 to 1,000 tons per day of CO_2.

Question: What is the emission of water vapor?

Peterson: I don't know what the water is -- there is no reliable way of measuring it. It is likely the most abundant of the gas emissions.

Question: Where can we learn about the hydrologic studies?

Peterson: The Water Resources Division has published a number of circulars. They should be available in the USGS Monthly Publication List, or write to the Vancouver office and information can be provided.

Question: What is causing the thrust faults?

Peterson: We are not exactly sure what is causing these. It is related to the magma column moving upward in the edifice. Somehow the magma from below pushing up on the dome is translated into movement in the adjacent rock underlying the crater floor. This is a problem being worked on and analyzed. We do know that the thrust faults have become a very useful prediction tool for the short and intermediate term forecasting of the next dome-building event.

ROLE OF THE U.S. FOREST SERVICE AT MOUNT ST. HELENS

Jerry J. Brown, Director
Cascades Volcanoes Emergency Coordinator Center
Gifford Pinchot National Forest

SUMMARY

March 20, 1980, began like almost any other late winter day for Forest Service personnel working on the Gifford Pinchot National Forest. Before the day was over, the routine was shattered as Mount St. Helens began to awaken from its 123 year rest. Forest Service personnel had little inkling of the challenges, heartbreak, and frustrations that lay before them in the coming weeks and months.

Since the volcano was principally on lands administered by the U.S. Forest Service, it was natural they would have an early and permanent role in preparing for the coming disaster and its aftermath. Other factors, including long experience in organizing for and dealing with forest fire disasters, an extensive in-place radio network around the volcano, and an in-depth knowledge of the surrounding countryside, were also large contributors.

INTRODUCTION

The Mount St. Helens complex lies on the western edge of the Gifford Pinchot National Forest. The Forest Service has had a presence in that area since 1897 as managers of federal trusts lands. The Gifford Pinchot National Forest was established in 1949 and encompasses an area from the Columbia River on the south to the southern boundary of Mount Rainier Park, on the north. It contains about one and a half million acres.

The Forest Service mission in normal times is the protection and management of the national forest lands. To do that, we practice the management philosophy called multiple use. In the simplest terms, that means we blend all the various uses together for the best utilization of the land and resources. To make the multiple use concept work the Forest Supervisors of the individual Forests have a great deal of administrative authority and autonomy; they run their own show. They have broad based laws, policies, and guidelines for their activities, and these provide a great deal of discretionary authority for the Forest Supervisor to tailor management to the needs of the land. This includes the protection of life and property, which became of extreme importance with the advent of volcanic activity at Mount St. Helens.

SETTING

First, a little about the setting around Mount St. Helens. Prior to May 18, 1980, this was the premier outdoor playground area of the State of Washington or at least southwest Washington. The beautiful conical shape of Mount St. Helens loomed over Spirit Lake. Many organization camps and resorts dotted its shoreline, and the area was covered with an evergreen forest mostly of old growth Douglas fir, hemlock, and noble fir. Additionally the area was located close to major population centers, only a short drive from Portland or Seattle.

The management of Mount St. Helens was complicated by intermingled ownership. Sitting close to the western boundary of the national forest, Mount St. Helens has a lot of private in-holdings around it. Immediately to the west was principally Weyerhaeuser

land, which was only about three miles distance from the volcano. On the mountain and to the north alternate sections of land were also owned by private industry, primarily Weyerhaeuser, Burlington Northern, and Washington Department of Natural Resources. There were also a number of mining claims that dated back to an old mining boom about the turn of the century.

The area was basically without roads to the north of the mountain on the National Forest lands and was managed mostly in the natural state. This includes the area around Spirit Lake and for 12 to 13 miles to the north to the vicinity of Green River. The south flanks of the Mountain had been logged both by the Forest Service and the individual private owners. The southern portion of the mountain was well roaded and accessible. To the west Weyerhaeuser had developed a very extensive road system to harvest the timber on their holdings in that area.

BEGINNING OF VOLCANIC ACTIVITY

March 20, 1980, was just like any other March 20th we had experienced in the Gifford Pinchot National Forest. It was quite a routine day. Things were going on at pace; people were going about their regular work. About noon, things began to get a little unraveled but not seriously. We experienced our first earthquake under Mount St. Helens. Little did we know that it was the beginning of a new experience for us. We did not connect it with any volcanic activity at that time. We were more concerned with avalanches. We went about our business of guarding the public against that avalanche hazard. That was the start of a constant series of earthquakes. I don't have any idea how many occurred between March 20th and March 27th, but it was a lot.

About the second day, Steve Malone called from the University of Washington and said that there was something interesting going on. He thought that the earthquakes were possibly related to volcanic activity. We've never had to deal with an active volcano before. At that time, we visualized a crater opening in the top of the cone with smoke, steam and rocks shooting up in the air and possibly lava pouring down the sides, ultimately resulting in a serious forest fire problem. About the 25th, there was a meeting with Don Mullineaux. He was co-author of the U.S. Geological Survey bulletin about the hazards of Mount St. Helens. After the meeting we knew we were in more trouble than we originally anticipated. We were told about mudflows, tephra, and pyroclastic flows. We discovered that the problem was not exclusively a problem for the U.S. Forest Service. It was going to include a lot of people because the projections for damage extended well out on the private lands. It became somebody else's responsibility once it was off the National Forest land.

MANAGEMENT PREPARATION

This prompted us to call a meeting on the 26th of March in our supervisor's office in Vancouver to discuss the situation. Those attending the meeting included the sheriffs of the three affected counties, the Washington Department of Emergency Services (DES), the State Patrol, the Corp of Engineers and private agencies such as Portland General Electric, which was concerned about the Trojan Nuclear Power Plant, and Pacific Power and Light, which was concerned about its reservoirs. There were about 26 agencies represented. Organizing an effort that includes 26 agencies, basically strangers to each other, presents a serious problem. After Don Mullineaux discussed the potential volcanic hazards, we decided to move along with some contingency planning. A conclusion of that meeting was that the Forest Service would take the lead in the contingency planning, coordinating the effort.

There were several reasons for the selection of the Forest Service as the lead agency. The principal reason was that the mountain was mostly on National Forest land. We also had capabilities that no one else had. We had an aerial surveillance capability. We had contract aircraft so we could fly the mountain on a more or less constant basis. In fact, we did for 24 hours a day for many months, rain or shine.

We had an in-place radio network that was to prove invaluable later. Unfortunately, the radio network was strictly a Forest Service radio network and did not really accommodate the needs of the sheriffs or other agencies. We had to do a lot of adjusting in order to have a reliable communication system around the mountain.

We also had search-and-rescue plans coordinated with the county sheriffs. It is really the responsibility of the sheriffs to conduct search-and-rescue operations, but in many cases the sheriffs are not well equipped to conduct these types of operations in wild lands. To facilitate their operations we usually furnish certain kinds of services for search and rescue in wild lands, such as radios and guides.

Lastly, one of the reasons we were selected was because we had experience with emergencies. Although the Forest Service had not dealt with volcanic emergencies before, we did have a lot of experience with forest fire emergencies. Through the years we have developed a good capability to mobilize a lot of people, in the thousands, on very short notice with equipment and radio systems to deal with forest fire emergencies.

CONTINGENCY PLAN

There was no rule book in the Forest Service for dealing with volcanic eruptions. We were soon in the position of writing the rule book, as far as emergency response was concerned. We developed what we called a contingency plan which consisted of coordinating statements of who was going to do what, when, and how. For instance, it outlined the sheriff's responsibilities, the Forest Service's responsibilities, and the Department of Emergency Services' responsibilities. The writing of this plan was momentarily interrupted by the excitment of March 27th when the volcano first erupted.

The contingency plan was a coordinating instrument and we had several basic concepts we wanted to develop with the plan. The headquarters for emergency operations was going to be at Vancouver. We assigned a high priority to a good radio and telephone communications network. We identified what we were to call the "core management group," consisting of the key agency representatives to act as a board of directors and pull the whole thing together. Also, we selected a name, the Emergency Coordination Center. That has since been shortened to the ECC.

The eruption on the 27th, as I noted earlier, interrupted our planning process, but it was advantageous in that it erased all doubt that Mount St. Helens was in fact an active volcano. Up until that time, the geologists were suffering from a lack of credibility. I suppose that is not an unusual phenomena, when you consider how you would probably react if a total stranger showed up on your front doorstep and announced that you had an active volcano in your backyard. That is just a little hard to swallow. At any rate, when the news of a volcano spread, not too many people could visualize the seriousness of the potential hazard as described by the geologists. Much of the public viewed it more as a curiosity than as a hazard. It took time for the geologists to gain acknowledgement that they knew what they were talking about

EMERGENCY MANAGEMENT

Another problem for the geologists was the media which, of course, was clamoring for news. This was the greatest story in the Northwest in years. It gained national and international attention for weeks. If the USGS representatives in Vancouver did not give the media a good story or what they thought was a good story, something to sell newspapers, there were plenty of other geologists willing to voice their opinions. There appeared to be no unanimity among geologists. This led to a great deal of confusion on the part of the agencies. The USGS would tell us one thing and we would read something different in the paper. We soon recognized the folks in USGS were the experts and we put 100% reliance on their opinions and forecasts. Certainly other experts were available, but there just was not enough time to allow a large body of scientists to sort out their various opinions and reach a unified opinion.

With the eruption on the 27th, there began a constant round of meetings. We often finished one meeting just in time to run down the hall to the next one. Days ran 22 hours, sometimes 24 hours, for the Forest Service people, the geologists, and the sheriffs office. Fatigue became a great factor. We had to deal with the communications problem, logistics, search and rescue, evacuation, area closures (that was to become and still is a very important aspect of volcano management), and the various legal authorities we all had to work under.

In the early stages of the eruptive activity, we took several closure actions that led to questioning of our legal authorities. Our problem here was that time was short and we just did not have the time to wait for legal opinions. Our objective was to keep people out of harm's way. Since those early days, we have clarified all the legal issues and our operation is fully within legal authorities.

It was during those early days that we received many telephone calls from attorneys and others with inquiries as to our authority regarding the area-entry prohibition then in effect. Our stock reply to our caller evolved into a statement about like this, "We are trying to prevent people getting killed. You find the authority that prohibits us doing what we are doing."

This all seems like a poor way to handle the situation, but we were tired, our tempers were short, and there just was no time available for debates of this kind.

There were several instances where political office holders brought pressure on us to relax our closure restriction enough to allow certain individuals and organizations into the area, but we successfully resisted these pressures too.

Another big impact was the media. We did not realize how interested the media was going to be in this whole situation. After the representatives of the USGS arrived, they were on national television almost every evening for awhile. Telephone inquiries into our office were so numerous that we could not use our telephone system even though we had a telephone system that was capable of handling more than a hundred incoming calls at a time. It was difficult to call out of the office, and the people who needed to call us could not get through. We finally resolved that situation by moving the media operations of the Emergency Coordination Center completely away from the Forest Service office, to a motel nearby where there were large conference rooms. We had a battery of telephones installed and we were soon able to retrain the media to direct all their inquiries to that facility. We conducted twice daily press conferences to keep people informed with what was happening.

By mid April, the Emergency Coordination Center was in full operation. We had a radio system and a telephone system with dedicated lines to the various emergency agencies such as the sheriffs' offices. The sheriffs had representatives in our office on a full 24-hour basis. As it turned out, the Emergency Coordination Center operation was to provide the overall leadership and direction of the emergency effort, to establish a 24-hour monitoring service, to provide communications monitoring, and to coordinate the air activities. There was a great deal of air activity around the mountain and at times flying was almost as dangerous as the volcano. We worked hard with the Federal Aeronautical Administration to establish effective control of the air space around Mount St. Helens.

We provided an agency coordinator whose job it was to communicate with all the other agencies, keeping them abreast of what was happening and common problems. We had the job of administrating the Forest Service closure area, that portion of the area that was under Forest Service jurisdiction. Most importantly, we had the responsibility of providing the emergency warning. We had a network set up with communications to the University of Washington's seismic center. The geologists kept us constantly informed. We were able to get good readings on what was going on, particularly after May 18th, to provide adequate warning. There was one instance when some people would have been killed had our emergency warning and evacuation procedure not worked. It worked

quite well and we were able to evacuate people from around the volcano in about twenty minutes.

That is where we were in mid April. Then Mount St. Helens became quiet. There was a great deal of pressure from people to open up the area and return to business as usual. The fishing season had opened. The snow was melting and the land owners wanted to get back in. Finally the 18th of May came and that erased all doubts of the volcano's destructive potential. We were in business and that's where we are today.

Figure 1. Emergency Coordination Center is composed of two trailers - larger trailer contains:

- Dispatch room where volcanic monitoring and warnings are initiated
- Forest fire dispatching and brush disposal business is conducted
- Offices for volcano, fire, USGS Hazards Coordinator, and Public Information Officer
- Teletype and computer room
- Conference room which becomes media room during eruptions
- Public information office which is open daily to answer the many questions we receive about the volcano

Smaller trailer, far right of the picture contains:

- Agency Coordinator's office
- Other agencies and companies have desks and phones located here to man during eruptions

Figure 2. Dispatch room in large trailer. Both desks have multiple channel radios. Dispatch boards are mounted in back by windows. Telephones on back and right wall are either direct "hot line" phones or state and Federal NAWAS phones.

Figure 3. Seismograph and television located in the dispatch room. The camera for the television is located five miles north of the crater. The closed circuit live television coverage was very useful as a monitoring tool, providing real time viewing of eruptions and quiet periods. We make a videotape record which the scientists have found useful.

Figure 4. Computer terminal and teletype.

Figure 5. Conference room and media room. Mini-news conferences and briefings are given here. The PIO's permanent office adjoins this room.

LOCAL GOVERNMENT'S EXPERIENCE AT MOUNT ST. HELENS

Les Nelson, Sheriff
County of Cowlitz
Kelso, Washington

Thank you, I feel like I'm on a two-man, low-level bombing mission with one opportunity to get the job done and I've got 25 minutes to tell you about 15 months. A lot has been covered by previous speakers and some of it will be repetitious -- but that's the way I learned my multiplication tables.

On or about the 25th of March, 1980, my office received a call from Vancouver stating that there was going to be a meeting there. It was an interesting thing. We were watching the mountain. I used to be able to see the top of it from my office window. The question was asked, "Well, who was going to be there?" Bear with me, because I'm only trying to make a point here. The Forest Service was going to be there. I've heard about them; they're the guys that wear Smokey Bear hats and tell us to prevent forest fires. DES (Department of Emergency Services) was going to be present. They're the folks up in Olympia that come down once a year to tell hunters not to get lost. The USGS was going to be there. Well, I remember seeing a picture of those guys in NATIONAL GEOGRAPHIC once. They're the guys who run around with little hammers pecking at rocks and making notes in books. The Department of Transportation was going to be there. They're the guys that drive around in yellow trucks all day picking up paper and looking through a transit at each other. The County Commissioners -- I was familiar with them; they're the people who give you a little bit of money and then give you heck about the way you spend it. The National Guard -- they're the guys that have the bunch of kids that dress up like soldiers on weekends; they carry bayonets and look like a walking rummage sale. I don't know what they do -- just have fun, I guess. State Patrol -- we were familiar with them, naturally; they're the guys that drink coffee while we cover their accidents. Anyway, believe me, we learned that some of those things were bad concepts and just smart aleck remarks.

We have learned to have a healthy respect for other agencies throughout all this thing. We learned through this drill what their capabilities were and what their restrictions were, what they could do and what they couldn't do, and what their departmental philosophy was. We learned that other people march to a different beat of the drum. We learned to communicate, which is one thing that we weren't too good at before.

We dealt with turf protection: "It's my county"; "I'm the boss here"; "I'm the County Commissioner." We dealt with lack of knowledge of other's capability and mutual lack of understanding. We dealt with some muscle that was being thrust upon us by people who would call up and say, "I'm important and we intend to get in there," and this and other things. Politics played a part in it that was difficult to deal with at times -- the whole gamut. But we did, as I've said, learn what resources that other people had and we learned to have some understanding about their problems.

We learned some quotations. Here are some of these quotes that we dealt with -- I only jotted down a few of many. "I'll have you know I'm the right arm of the Governor." That explains several things -- which wasn't the intent, at least, of the person who told us that. "Nobody can close

the state highway except the Department of Transportation." "We don't take orders from anybody." "Who's in charge around here?"

What I'm telling you is to get acquainted and to learn a common language. That was eluded to by people who have been up here before. I think geologists need to write a dictionary. I think I've finally figured out that alphabetically at least, "magma" comes between "alpha" and "omega." You'll never be sorry if you spend some time with people. We look to you people as resource people. Learn to understand what people can do for you.

I guess I'm talking to emergency services people here. The idea is to know what is available to you and how that can be handled. Not one hour of planning will ever be wasted, because to fail to plan is to plan to fail. I've learned that. One of the reasons I say that, as I get on into this, is so that you may be able to have a better understanding of that.

We learned that when a mountain has too much Sasquatch spaghetti and has heartburn, it throws up something awful. You never really know what you can do until you're put to the test. We learned that lesson if nothing else. If you think you can or you think you can't, you're right. That's about the size of it.

I've had some new words added to my vocabulary -- "pyroclastics," "mudflows," and all of those "harmonic tremors." I've got a picture of an old salt cowboy on the wall that says "There's a hell of a lot of things they didn't tell me about this outfit when I hired on here." That's kind of the way I felt about it. I look back and I don't remember anything in my job description that said anything about volcanoes either. I guess, if I ever run for sheriff in an area other than the one that I'm in, which is not likely, it won't be located between a volcano and Trojan Nuclear Power Plant.

Had anyone asked me, Can you handle an emergency this size with your department? I'd have said, Heck no. We're busy answering dog calls and chasing burglars and all those things. There's no way that we can. But you never really know what you can accomplish until you're put to the task. I don't want to be repetitious but I really want to make that point. We thought we had our hands full with law and order.

Our problems started, of course, on March 27 -- this coordination business. We had a problem of unknown magnitude and no past history to give us any guidance. Someone mentioned that there had been a book written and it wound up on the shelf with the Trojan plans and a few other things. It wasn't in our office. We thought we were going to have one of those Roman candle mountains and that it was really going to be interesting. I could sit right there in my office and watch it. It didn't quite turn out that way.

People were coming in hoards -- the first live volcano in one hundred and thirty some years. As sheriffs, we were faced and charged with the responsibility for the protection of life and property. Sightseers and other people did not believe that there was any danger. Of course we didn't know what kind of danger we were facing either. There was the development of the Governor's proclamation, the "red zone" hassle, and it was really a hassle. Where's that guy who said that the road blocks were a political boondoggle? I just want to tell you, you were right. They were a hassle. They were a hassle for all of us. Sightseers would tell us: "This is a free country." "This is a public road." "I'm a property owner; I have a right to go up to my property and get my earth stove out of there." "I pay taxes on that set up." Store owners were unhappy; hunters were unhappy. Fishermen and tourists were turned back. They were trying days on foreign soil for those of us in law enforcement that tested our powers. We had to draw the line somewhere.

We became very well acquainted, as has been indicated, with the USGS geologists. I hope that other people in your area can get to know you. We got to know the geologists on a first name basis. We had a lot of coffee and listened to them. I certainly listened to them after this thing had gotten down the road.

We kept facing all kinds of opposition to what we were trying to do, but we had to

dig our toes in and stand firm. Ordinarily, law enforcement has the advantage of working with written law. As a matter of fact, at work, that's the guideline to work with -- written law. But with Mount St. Helens steaming up, we were building a boat and rowing at the same time; so we made some of our own laws. People said, "You can't do that; I'm going to call my attorney." We said: "Good, that'll get you off the phone; we have other work to do." "Just have at it. We'll see you in court down the road somewhere."

In Washington, we don't have a mutual aid agreement as you have in California, but the sheriffs of three counties around the volcano included two other men who were exceptional individuals as well as good sheriffs, in my opinion. (I wouldn't say so if they weren't, since they're sheriffs). We just kicked down the county boundaries. We went ahead and cross-commissioned our people in the three counties, and county boundaries were no longer of interest because we had a mutual problem.

We had a lot of good people working with us. We worked with a lot of good people outside of the agency. You know you can get a lot accomplished if you don't expect to get all the credit; and that's kind of where we were coming from.

Perimeter control of course was, as I've talked about, a big problem to us. The Forest Service was most helpful in many ways. They had a lot of good people working there at that time and other people just as capable. One man that I always remember was Paul Stencap, who has since retired, and I don't blame him. Anyway, Paul was a fire boss and in his dealings with a lot of people and putting up with a lot of guff, he was very effective.

The Governor did set up a red zone. We had a lot of problems with that. Where was the zone to be set? That's been pretty well explained. At one point in time, the Spirit Lake highway, and I'm talking about the black top (I'm not talking about the dirt on either side of it), was in the red zone, which ran up there to about 33 miles where we had a lot of tourists piling up. Unfortunately, we had already built a turn-around back down the road several miles. I'd gotten Dick Nesbit from Weyerhaeuser to go in there with his rig and his big equipment and build us a turn-around. We were going to move that zone back to that turn-around on Monday morning. So, we missed; as things would have it; we were only three hundred yards from the edge of the single area. Had we gotten it back, we may have saved some more people. We just missed by that much.

Let's talk a little bit about some planning. I'd like to think that you people, either through emergency services or whatever, get acquainted with the people that you're dealing with. I don't know how many of you know of your chief law enforcement. I don't know what the laws are down here in this area in California as to who is in charge in those kinds of situations. As I said, we had a lot of muscles flexed up there. "I'm in charge. I'm from the Governor's office"; or, "I'm for here or there." But, it was kind of hard to find some of those people on May 18. Then they said, "You're in charge," you know. "It says right here in the book!"

In this planning business, one thing that is overlooked is the reinitiation of teaching people to be self-reliant. We put out a lot of pamphlets. We did a lot of things along that line. We talked to people up there along those drainages that were on the hazard zone. We spent a lot of time with them and put out pamphlets, and they became self-sufficient. It gives me a thrill even today to think about looking out my window the morning that thing blew. I must have seen it within a minute of the time that it started. I called the office and they said, "Sheriff, remember that note on your desk that said 'I must hurry for there they go and I am their leader'? They're already gone."

The reaction from the people and from the officers was fantastic. The people saved themselves. All they needed was that signal that it was time to go. They had their ditty bags packed and left.

We had established a ring down system in some of those areas up there along the dead-end roads. We figured it would save us a little bit of time. Now we're not talking about a lot of phones like you would have to deal with down here. In 17 minutes, that

ring down system had been effected and everyone had been notified in that area. In addition to the assignment of our personnel, we had gone to the extent of writing a plan. After talking with the USGS people, I had become convinced that something was going to happen up there and it wasn't all going to be pleasant. So we went to work. We did not write a long plan or an elaborate one. The administration had put a plan together.

The officers were tuned in to what their responsibilities were. They were assigned to a specific area that they could cover adequately. They were in there.

It became a "no-no" in Cowlitz County and the other counties on the other side of us to use a high-low siren. We decided that would be the signal because people hear sirens all the time, and they don't pay them much attention. Now, if you hear that high-low siren, you're kind of in the position of the guy, a reporter, who was riding in an airplane. It was a two-man jet, and the pilot went through all different things that were in this guys' cockpit. Finally, the guy said, "What is this little ring down here?" "Listen to me, that's the ring that pulls the cord that fires the ejection seat, and if I tell you to eject, don't say 'huh?' because you're going to be talking to yourself."

We had that down pat, really. We did not have one band-aid or dented fender with all those people that had to move out of there. We had loss of life, but they were people that were beyond the warning zone. There were hundreds of miles of just all kinds of roads up there. It was not possible to keep people out of there until we finally got some laws that had some teeth in them, administrative laws. We were able to warn all those people and move everybody that was in the zone. It worked slick and it was relatively simple.

Being innovative is something worthwhile. We kind of get into routines. We established our evacuation centers, Red Cross, of course. We had some 66 agencies involved. That's even more than the 37 mentioned by the previous speaker. Evacuation routes -- yeah, they're great as long as you've got bridges, but we didn't have any left, once that mud came through there.

We developed a cable view interruptive system up there. What it really amounts to is that we go in and punch about four buttons in my office or in the DES office (I'm the local Director of Emergency Services as well as Sheriff). It doesn't make any difference what's on TV, and I'm always hoping it won't happen right at touchdown time in the football game. For 90 seconds, your television is going to turn gray and we can talk to anybody that happens to be watching their television.

A radio station up there has been selected because their power doesn't stay on all night. We have the capability of going in and turning on that radio station in my office and using that radio station until they get people there to man it so I can talk to the people. People left their radio's on turned to that station. If we came on the air it woke them up.

Trojan has put in a hundred and some sirens around in a warning system. They have agreed that those sirens can be used for anything in the way of an emergency. We have that kind of an agreement with them. We're going to try to get that extended on up the drainage since no one can hear it now up in the Toutle country. As perhaps some of you may know, the volcano is in Skamania County, but we got all the drainages off of, as I refer to it, Sheriff Bill Closner's sick rock.

We deal with the people problem as well as the Forest Service did when they used to have roads. They still got roads on the east and south side, but on the west side, we still got the problem.

Do you ever stop to think what the county extension office or church organizations, for that matter, can do for you? The Lions Club in Longview, because of the flood which was an aftermath of this thing, organized the block watch situation. The City Police know where the people are that are handicapped and can't really help themselves. There are a lot of good volunteer organizations.

I'll touch quickly on the news media. We had our problems. I've told people that I used to carry a little mirror and look around

the corner to see if there were any of the news media out there, because you just couldn't get your work done -- we did have a couple of things to do. But they can be an ally without a doubt. That's the only way you're going to be able to tell the people out there what's happening. Not all of the news media are good people. Even Noah's Ark had a couple of turkeys on it.

I also found out, and I really believe this, that the public can handle good, solid information. People feel that if the Sheriff in Cowlitz County tells them something, they can believe it. That's kind of a heavy burden at times, if you'll stop to think about it, but it helps to keep down the rumor factory.

We wanted to educate our people. We put Plectron systems in our schools. Industries have them now. We can trigger that from the Sheriff's office, so they know if we have a flood situation and that's basically an aftermath situation, but a very serious problem as far as Cowlitz County is concerned.

Be prepared. I would certainly suggest, at least to those who are here other than geologists, that you may have to do some of the things Jerry Brown said. Just do them and then worry about it later.

The tourist situation was difficult to handle. Some of our people became somewhat brusk, I guess you'd say. We thought a couple of times we should have looked up a Texan that showed up there. He was up there looking at the volcano, and Bib Nix, one of my deputies, was standing there, kind of talking to him. Bib said, "Bet you haven't got anything like that in Texas." Well, if you're smart, you'll learn that you can't talk to a Texan. The Texan looked down for a minute, and then said, "No, but I'll bet we got a fire department in Amarillo that could put the damn thing out."

I talked to a man with the Red Cross. Missing persons lists are a terrible thing to have to deal with. And you people in some areas would certainly have a bigger problem than we had. One of the things that happened to us was that inquiries from the Red Cross became intermingled with our missing persons lists, and so we wound up with lists that were not really true. We've got two or three people on the list today that are only names, no follow up. We did not do a good job of recording who the call came from. Now we have developed a good missing persons form that would be helpful. Incidently, here I will say that if there is anything that we can do to be of assistance, we're more than glad to do it. It's extremely important to obtain information before you let that person hang up. The FBI Identification Team's help was indispensable. This is one of the many books (emergency plans) that many people had an input into. The Forest Service actually printed the book. Later on, after the mountain blew up (I've lost track of time and sessions), we decided we needed this thing in one more full printing. So we had a meeting of the necessary people and put together a task force. We certainly learned to work together; believe me. The task force said, "Well, how much time do we have?" And we said, "We don't care how long you take, so long as you have it done by next Friday." That was in one week. On Thursday, my DES coordinator walked into the office about 4:00, and plopped that thing on my desk. They had eaten a lot of hamburgers because we just penned them up there; they were sequestered like a jury almost.

The mountain blew up again that night about 9:00. To show you what planning had done for us, come daylight the next morning, they were set up in Toledo. They were ready to do it again.

We had about 34 agencies involved at the air operation in Toledo. I can run through some statistics real quick. This is just a part of the rescue end of it. There were 192 service people and sheriff officers. For the air activities, they flew 577 sorties with 1,111 aircraft hours, and we used 258 aircraft. We had 1,976 personnel at Toledo. We used up almost 19,760 man hours up there on that Toledo operation for rescue and searching for missing people. I don't remember how much jet fuel we burned, but it was a lot.

IMPACT OF THE ERUPTIONS ON CITY GOVERNMENT

Betty L. Edmondson, Mayor
City of Yakima, Washington

SUMMARY

On May 18, 1980, Mount St. Helens erupted and spewed some 600,000 tons of volcanic ash on Yakima, Washington. The City was faced with a highly unusual and potentially disastrous situation which stretched local capabilities and resources, both public and private. City, county and state agencies had prepared various emergency plans, but few of these had ever been tested, particularly in a volcanic emergency such as this. The immediate and potential hazards from the "unknown" put to test the city's administration/elective personnel faced with the responsibility to provide basic services to the populace. Some of the areas which had to be addressed were:

1. Keeping the public informed via media announcements.

2. Monitoring and maintaining domestic water and sewer services clogged with volcanic ash.

3. Ensuring public safety/emergency response capabilities.

4. Ensuring adequate airport accessibility for personnel and material support.

5. Restoration of crippled City services (i.e., transit and refuse collection).

Providing for citizen's health and safety, street cleanup, and maintenance of business activities was challenging, for there was no known game plan. Such an event had never happened before! In a relatively short time, the citizens of Yakima banded together with their neighbors in a coordinated emergency effort to restore order and to carry on with their lives in as normal a fashion as possible. A major element in this coordinated effort was the task of cleaning up the ash fallout in cooperation with municipal crews.

Besides the physical problems of the ash fallout, local officials encountered administrative and financial challenges as well. Private contractors and public works crews from other jurisdictions had to be contracted for and paid. There are still some unresolved issues: namely, (1) the need to reform FEMA rules and regulations for this special type of disaster; (2) the enormous costs to local government that are not reimbursable due to FEMA's misguidelines; (3) the undefined long term effects of ash fallout; and (4) the yet to be determined effects of long term preparations for future volcanic eruptions.

EVENTS OF MAY 18

When Mount St. Helens erupted Sunday morning, May 18, 1980, there were two distinctively different types of impact in two separate areas. In the immediate area of Mount St. Helens, the eruption was catastrophic for human, animal and plant life due to the directed blast, burial and eventual flooding by volcanic material and water. Fortunately the area was sparsely populated.

A different type of impact was felt in eastern Washington, where winds transported some 200,000,000 cubic yards of volcanic ash to rain down on modern cities and towns with complex public utility and transportation networks. Forty-nine percent of the land area of the State of Washington, chiefly five counties in the eastern part of the state, was affected.

Yakima Valley lies about 84 miles northeast of Mount St. Helens. In the City of Yakima, population 50,000, no one was prepared for what happened on May 18th. About 10:00 a.m. the first cloud of volcanic fallout reached the city. The cloud was dark and overpowering, accompanied by lightning, thunder, and a strong smell of sulphur. In a short time it was pitch dark and silent, as during an eclipse, except for the sound of dry rain. The city was in darkness for the next 16 hours.

The dry rain was volcanic ash. Three types fell alternately on the city: dark gray sand, medium gray sand, and light gray, cement-like dust. All three grades were gritty and light, difficult to sweep or shovel, especially when dry. It was exceedingly abrasive and harmful to mechanical equipment, especially the motors of vehicles and aircraft.

CONSEQUENCES

The ash fallout was crippling to cities. Yakima received 1-2 inches, Moses Lake, Ritzville, and other smaller municipalities in central Washington received up to 4 inches. Spokane, 255 miles away from the eruption, received 1/2 to 1 inch of mostly the light ash (volcanic dust).

It is estimated that some six hundred thousand (600,000) tons of the ash was deposited on Yakima. Nearly 16,000 tons of ash was cleared from the airport runways alone.

In Yakima, there had been essentially no planning for or past experience with such an ashfall. City officials tried to contact both the local and state emergency services offices for information, but on that Sunday morning, these offices were either closed or unprepared to deal with the situation. The ashfall had caused closures of all major highways and the Yakima Airport. The city found itself alone to cope with the situation.

The formal Emergency Broadcast System was not activated because the local station responsible had no staff that Sunday who really knew how to operate that equipment or knew what to do. A local "all news" radio station provided around-the-clock information, and in the first hours of the emergency proved to be the most useful vehicle for dissemination of information. Now, as a result of the May 1980 experience, the Emergency Broadcast message is regularly taped on a rotation basis by city and county officials. This practice not only serves as an on-going reminder to them to maintain concern for emergency preparedness, it also ensures up-to-date announcements by voices familiar to the citizens.

EMERGENCY OPERATIONS

A command post was soon organized at City Hall and staffed with emergency representatives, including the Mayor, City Manager, County Health Officer, representatives from the county government, Emergency Services, and local businesses and schools. Previously, city management staff had developed a strategy to respond to emergencies, and, with only minor modifications, the command post group followed that approach. The main concerns of this group were as follows:

1. To inform and calm the public.
2. To monitor the public water system and prepare for unusual maintenance repair actions.
3. To monitor the sewage treatment system and prepare for maintenance and repair actions.
4. To assist law enforcement and ensure public safety by ensuring that police and fire vehicles were in working order.
5. To close and monitor the airport, city transit system, refuse collection services, etc.

These were the immediate concerns, and each department was asked to develop its own emergency staffing plan and determine the basic level of operation support to maintain basic essential services. There

was really no reason to shift from the traditional management patterns.

Everything was virtually halted -- roads closed -- no buses, planes, trains, mail, refuse, school, deliveries, etc. It soon became obvious that the sewage treatment plant could not continue to operate under the load of ash. With the concurrence of Federal Environmental Protection Agency and State Department of Ecology, officials, it was necessary to discharge partially treated sewage into the river while a bypass was being constructed. This was closely monitored by the state and federal health officials. This concurrence was necessary to prevent possible future dispute about the necessity of taking such action.

Emergency operations were conducted from three headquarters in the city: City Hall was the main headquarters for directing and coordinating all efforts; the city maintenance yard and shop area was used as headquarters and staging area for the equipment and manpower brought in from other cities and counties to help with the cleanup; and the School Administration Building was used as headquarters for the Neighborhood Cleanup Campaign. School staff, as organizers, assisted by personnel from Red Cross, Chamber of Commerce, and others, helped calm fears of the public as well as assisting in cleanup.

It was soon obvious to city officials that our local government resources in terms of equipment and manpower were inadequate to address the magnitude of the massive cleanup effort facing the city. We had to obtain immediate outside support; so Yakima contacted other municipalities and counties together with private contractors. All totaled, the amount of equipment and manpower brought to assist the city for the ashfall cleanup was ten times greater than our normal maintenance effort.

During the cleanup, Yakima suspended business activities. We closed off the central business district for 2 1/2 days to facilitate the cleanup of the area -- the streets, alleys, sidewalks, parking lots and roofs. The Clean Air Authority suspended clean air regulations for two (2) weeks to facilitate clean up activities. The help of the military was sought, but we were refused assistance even after the Federal Government had declared that a state of emergency existed.

At this writing, the City of Yakima has expended $1,900,000 for cleanup alone. The Sewage Treatment Plant costs are still not known, but are estimated at $500,000 to $2 million. Because of a federal-state agreement, FEMA will only reimburse 75% of eligible costs of declared disaster incurred by cities. The cities are actually getting approximately 65% reimbursement and the state government has escaped budgetary impact. The city feels FEMA regulations were not designed to respond to this type of emergency. Based on the regulations, the citizens of Yakima will have to foot the bill for $500,000 to $2 million, unless we can get assistance from the State Legislature.

In the initial aftermath of the Mount St. Helens disaster, the federal and state governments requested estimates of economic loss to our area. It is important to give as accurate assessments as possible following any disaster. Overly inflated estimates have a potential of creating even greater damage, and may prove troublesome to correct. They can even have devastating effects on the bond rating of a city.

OBSERVATIONS AND CONCLUSIONS

The management of a rapid clean-up campaign is stressful. The excitement of this challenge creates a type of euphoria which can readily lead civic leaders to over-react rather than to rely on the people and the existing organization. In looking back at the experience, I feel it important that those in charge stand back from the flurry of action and reflect on what it is that they are attempting to accomplish. In addition, it is extremely important for community leaders to maintain their health and spirit. The community looks to us for leadership and is quick to note a frantic or insecure appearance. Grandstanding should be left to others -- it is the responsibility of those in

charge to project an image of rationality, strength, and organization. Such attributes cannot be faked.

Local organized groups are readily available resources for help in organizing the citizens to get things done. Groups such as service clubs, the grange, churches, etc., are a great asset. The Director of the Library proved to be a great source of information -- using the resources of the library in an emergency situation is a must!

The eruption of Mount St. Helens on May 18, 1980 created unforeseen short and as yet unknown long range problems that are virtually impossible for any city's resources to accommodate. This natural disaster was unprecedented in our area and never before, at least in recent times, has the federal government been asked for financial aid after a volcanic eruption and its resulting ash fallout.

The eight days following "Black Sunday" were traumatic, hectic and even rewarding. Traumatic to see our lush valley oasis turned into a gray swirling dust bowl. Hectic trying to find answers and solutions to our new fallen challenge. Rewarding in the togetherness brought forth through this united community effort to dig out.

Many of us in local government have often said that that's where the action is -- in local government. When disaster strikes and the city government and community must respond, you find yourself on your own, depending on your own resources. The media was filled with the comings and goings of major political figures and their bold statements, but none of them were here, with shovels and equipment ready.

Emergency preparedness in Yakima today is well organized, and we maintain a constant state of readiness. The eruption of St. Helens has dramatically affected our concern and interests in emergency planning and organization.

COMMENT

Alex Cunningham: Thank you very much, Mayor. As Sheriff Nelson said earlier, "You always find out in certain situations who is in charge." Mayor Edmundson's experiences show graphically that, in an emergency, local government is always in charge. This is especially true in California. The Mayor's final comments made the point that I have been expressing throughout the State of California the last three years; that is, that local government officials have to "give a damn." So do state officials, and you have to start now! Disasters are going to occur, and unless you can get the local government people, who are the first line of defense, really cranked into action on these kinds of programs, the system will crumble. You just made the point for us: You have to start now! I agree with you wholeheartedly that many local officials know that disasters are going to occur; however, very few of them are willing to commit the resources necessary to be prepared because they think that the disasters are going to occur in somebody else's community or after their own term of office. So, I'm glad that you have shared your experiences and advice relative to this important principle of preparedness.

PANEL DISCUSSION II

EMERGENCY PROBLEMS FOLLOWING THE ERUPTION

Moderator: Alex Cunningham, California Office of Emergency Services

Panel: Jerry Brown, U.S. Forest Service
Betty Edmundson, Mayor, Yakima
Jack Kartez, Planner, Washington State University
Les Nelson, Sheriff, Cowlitz County
Don Peterson, U.S. Geological Survey
Don Mullineaux, U.S. Geological Survey
John Sorenson, Social Scientist, Oak Ridge, Tennessee

Richard Kilbourne: Has anyone come up with a way of solving the problem of overcrowding of the phone lines?

Alex Cunningham: We have that experience every time a disaster occurs in California. One that comes to mind is the PSA plane crash in San Diego which was a horrible disaster in which 144 people died, but in a rather localized area; about seven square-blocks were affected. That plane crash occurred at nine in the morning, and yet, we still were not able to get a line out of the area. I could call locally, but I couldn't call long-distance going out because of all the incoming traffic. I couldn't even get through to the Governor on the telephone that midnight. What I finally did was to call the California Highway Patrol on local and have them contact my office in Sacramento on the radio net, have them call me, and then patch me through to the Governor. The telephone system does have a way of handling overloads on the system by what they call a "priority service." The best way, however, is to get the cooperation of the news media so that they can request the public, over the emergency radio broadcast system, to please stay off the phone lines. That works for the local area, but it doesn't help to deter Aunt Mary from back in Buffalo from trying to call to find out if her sister or her son was affected. It takes cooperation on the part of the public.

Question: Is there any way that the phone company can close down incoming calls to the area so that only outgoing calls can be handled?

Cunningham: Yes, but they have to be careful on that because a lot of the incoming calls are responding to some outgoing calls when, for example, through our mutual aid system we put out a call to a contractor in the southern part of the state to move some equipment up and he is trying to get back to us. Again, it is a priority basis. Mayor.

Betty Edmundson, Mayor, Yakima: A more extreme case of telephone system failure occurred in Yakima where part of our telephone system was mechanically inoperative for a time. What happens then is that people turn to the radio. So, the radio says, "Don't worry." We got tremendous cooperation from the media in broadcasting our news and safety messages. They were constantly on the radio and TV. Some of the

messages were advice like "Shovel the ash from roofs." There was danger that rain falling on the ash would increase its weight to the point that roofs would collapse. So I think the alternate tactic is telling people to keep off the telephones and to use the news media (radio, and television) for information. That way the information doesn't have to be constantly repeated.

Question: To Dr. Peterson. To what degree has the water supply of the affected area in the Cowlitz drainage returned to normal?

Don Peterson: Many of the lakes such as Spirit Lake are still covered with floating logs, and it is a real mess. Many of the other lakes in the region are, indeed, that same way. The Toutle River is turbid with sediment all the time. It is badly contaminated. There is some danger, especially during the warmer months, of bacterial contamination, but nature heals itself. The lower reaches of the Toutle River have now partly cleared. There have been fish, salmon, returning up some of the drainages; however, during the seasonal storms, there is a lot of erosion and the rivers fill up again with sediment. There will be a constant threat of potential flooding through the coming winter season.

Question: To the Mayor of Yakima. What was the effect on the health of the citizenry of the fallout in Yakima?

Mayor Edmundson: I will address both mental and physical health. There was actually no harmful effects physically on the people of Yakima. Those that had respiratory problems dealt with the problem immediately. Whenever there is a dust storm, they are careful, so those people automatically took precautions. Health authorities found that the particulate matter was not harmful or detrimental to the citizens at large, but they were concerned about prolonged exposure. Masks were issued to protect citizens so there would be no harmful effects. The mental effects right at first sort of weeded out the people that could cope and the people that couldn't. The people that were affected by any type of trauma just had to leave and were shipped out -- probably one or two percent of the people.

It has had a lasting effect on City Hall. Since the eruptions, the people are so happy with themselves and the government about how they dealt with the emergency and cleaned up the city, we have had fewer complaints than ever before.

Jack Kartez: Let me add one piece of information. For those interested in the mental health aspects of long-term recovery from St. Helens, there was a year-long counseling effort, called Project Ashlift, by the Department of Social Health Services in the State of Washington. The project has just ended, and a report published.

Roger Martin: Dr. Kartez mentioned that a countywide civil defense oriented emergency coordination system encouraged by state and federal program was not effective in the Mount St. Helens emergency, and that the roles of emergency response fell to general purpose local government. In light of some sobering comments by Sheriff Nelson and Mayor Edmundson about how much worse the consequences of the eruption could have been, would you comment further on our present state of preparedness for an even greater catastrophic disruption?

Jack Kartez: FEMA works with states and counties to establish a general radiological preparedness plan -- a nuclear response plan. The plan, as of two or three years ago, basically involves moving urban populations in large numbers to outlying rural areas; for example, roughly 250,000 people from Spokane metropolitan area, which is about 330,000 people, would be moved south approximately 75 miles to the Pullman, Washington and Moscow, Idaho area. Local governments over the last couple of years have been briefed on this.

Betty Edmundson: That plan had nothing to do with this because that particular plan would move hundreds of thousands of people

from Seattle to Yakima. There really wasn't a plan of FEMA for a volcanic fallout that I know of. Their guidelines are not based on the type of emergency we had. That is why we had the problem of fitting the "regs" into what actually happened to those they had regulations for. It is important that some type of plan be developed regarding earthquake and volcanic hazards.

Alex Cunningham: The plan that we are talking about is the Crisis Relocation Plan currently being detailed in California by our Nuclear Civil Protection Division, and we have completed it for about seven or eight counties. Although this plan calls for moving people from a risk area in the event of nuclear attack to a host area, the same concept that exists is what is going to pull you through in a major volcanic emergency. If you have a general evacuation plan, you can change your direction of travel. As long as you still know where you need roadblocks, how many people you need, and more importantly, how you are going to set up congregate care centers outside the area, how you are going to house and feed these people, how you are going to take care of their medical needs, how you are going to take care of the law enforcement and fire protection in the new area as well as to still continue the protection for the old area, those concepts do exist and every state is working now with FEMA and local governments to prepare those plans. It is not something that we want to load on local governments and say, "Here, you do it." In California, we are detailing the plan, but we are doing it with the assistance and advice from local government. We are not laying a big dollar burden on them, but we are not trying to prepare it in the blind either.

Jim Davis: A question to Don Mullineaux. Is it true that the USGS did not use the terminology, "Watch," "Warning," and "Notice"? And if not, why not?

Don Mullineaux: Those specific terms are required in the Survey for use by our main offices in Reston, Virginia. We are required to issue a Notice of Potential Hazard as the first level of warning. That was done with the publication of our report in 1978. The next step, when the situation becomes more immediate, is the Hazard Watch. The next level, after such time as the monitoring or other information indicates that an eruption is imminent in terms of days or weeks, is the Warning. These levels of announcements go through a specific administrative procedure. On the site in Vancouver, and by phone before that time, we were trying to provide information locally useful, and at times it may have been different from those official pronouncements.

Clem Shearer: It is correct that the Survey issued an announcement with the label, "Hazard Watch," which essentially means that there is something active going on, and we will continue to monitor it, and as we get more information, we will continue to keep you advised. This is generally issued to the state Office of Emergency Services or, in some cases, to the chief geologist of the state and in a couple of cases, openly designated by government. The federal government insists that that terminology be used internally, but, in the field, in face-to-face confrontation, we don't insist that that terminology be used. I think it wise to use whatever one wants.

Don Mullineaux: Perhaps one way to explain it is that those notifications were made in the order mandated, but not through us at the volcano field office.

John Sorensen: I think another relevant point here is that even if those notifications were made, they would be lost under the barrage of information that would go out to the public through the media. Hence, they are not really relative distinctions.

Don Irwin–Office of Emergency Services: A question to the Mayor regarding the ash cleanup. What is the short-range and long-range economic impact on the Yakima Valley?

Betty Edmundson: There are two separate things, although I guess they could be the

same because you have to pay that half-million dollars back. The economics are good. We realized within three or four weeks after the eruption that there was not going to be any great long-term, major economic impact. The Mom-and-Pop operation, those types of things that don't have a lot of cash flow or depth, went to the Small Business Administration, and some could be helped and some couldn't. Operations that were marginal or uncertain anyway may have gone under, but, the valley, in general the agriculture, suffered no long-term impact or effects.

Don Mullineaux: May I put in a plug for volcanoes just very briefly? Most of the soil on which the agriculture had depended on there is very ash rich, so for the very long-term, the impact should be beneficial.

Question: How helpful would it have been if your city had had some warning as to what to expect from the eruption?

Betty Edmundson: I honestly don't know, but I completely concur with Mr. Cunningham regarding the importance of having a workable plan that can be formulated for or adapted to the local municipalities or counties. If we had known in advance and believed it, I think we would have known immediately the people to call for assistance. The people we were to call would have been there, and we wouldn't have lost so much time or experienced so much stress.

Get an emergency plan written and practice it. You can't live in fear for a long, long time. If nothing happens, you are going to forget the plan, so you need some ongoing "tickler" that is going to keep it alive. In Yakima, I'm called about every six weeks to do a taping of an emergency broadcast, and so are other people. That is in the back of your mind. When I leave this office, that mayor will be called. An ongoing plan needs everyday functions to be effective because emergency plans are otherwise going to be forgotten.

Alex Cunningham: Let me add to something that the Mayor said to the question that if we had a warning, would it have helped. Her answer was, "Yes, if we had known in advance and believed it." I can guarantee you that they probably would not have believed it in that case. Now, they will believe it, and now they believe it in California, only because it happened in Washington. Jim Davis and myself are deeply involved in earthquake prediction. Jim, as the Chairman of our Earthquake Prediction Evaluation Council, will someday have to come to me and say, "This one is valid!" The first time I go to the Governor, and we go to the press and say it is a valid prediction, people are going to respond to it "tongue and cheek." If we make the prediction and the earthquake occurs, the second time they will pay attention.

Nels Rasmussen — Office of Emergency Services: I am confused as to just who was in charge in the so-called "red area" and who was responsible for designating that, and who was responsible for controlling that area.

Jerry Brown: It was a joint operation. As I pointed out in my discussion this morning, part of the jurisdiction was national forest, part of it was the State of Washington, and through the State of Washington, county sheriffs. The effort to develop the "red zones," or more properly, the "closure zones," entailed a lot of effort. It was a joint operation that entailed a lot of dialogue between the agencies, with the geologists' expert input as to where we ought to draw the lines. This has become particularly important here in recent months, after the eruptions, because we have been gradually shrinking back, trying to return as much of the area to normal as we possibly can. The control activity has been a dual responsibility. The National Forest Service does a lot. We have relied primarily on the gate system to exclude the public from the area; the sheriffs, on the other hand, due to expense, have relied more on patrol in those portions of the zone that they are responsible for.

VOLCANO EMERGENCY INVOLVEMENT AT THE FEDERAL LEVEL

Robert C. Stevens
Federal Emergency Management Agency
San Francisco, California

ABSTRACT

By Executive Order 112148 of July 20, 1979, the President delegated the emergency management functions of his office to the Director, Federal Emergency Management Agency (FEMA). This includes the coordination of all civil defense and civil emergency planning, management, mitigation, and assistance functions of the federal executive agencies, as well as the administration of the Federal Disaster Relief Act of 1974, Public Law 93-288. The Director of FEMA, in turn, has delegated most of his authorities to the Regional Directors. Specifically, with respect to the Disaster Relief Act, the Regional Director has the authority to approve and fund disaster relief activities within his region after the President has made a declaration of "major disaster." PL 93-288 provides for federal supplemental assistance to the various states, local governments, and private relief organizations to supplement the efforts of these groups. All federal disaster relief is based on a declaration of "major disaster" or "emergency" by the President. The President reserves this authority to himself. The administrative procedure involved in obtaining a "major disaster" declaration requires a declaration of emergency by the Governor of the state involved, and a request from the Governor to the President federal assistance. This request is administratively processed by the affected Regional Director of FEMA, who evaluates need, normally based on field assessment, and makes a recommendation to the Director of FEMA. The Director of FEMA, in turn, processes the request to the White House with his recommendation. However, in every instance, the final determination is reserved by the President. If the President declares a major disaster, the law requires that he appoint a Federal Coordinating Officer who becomes the principal federal spokesman in the disaster area and is charged with overall coordination responsibility for all federal disaster activities including the statutory authority of the various federal agencies.

INTRODUCTION

I had the pleasure of being up at Mount St. Helens on the eighth of May for kind of a "Cook's Tour." We flew the mountain and were greeted by the USGS and the Forest Service and some other folks. Incidentally, the agency had been subjected to some criticism for not having taken a more positive role up to that time (this was ten days prior to the big eruption). At that time, my boss in Washington, John Macy, asked me if I felt we ought to be taking a more aggressive role, and I told him "no." I felt that the Forest Service and the USGS were doing an outstanding job, and I still believe they were doing an outstanding job. They were working very well together, and I didn't see any purpose at all to be served by interposing another layer of federal bureaucracy into the system. That is the position I took. Now, obviously, if I had been able to look into the future for a couple of weeks, I would have taken a very different position. At that time, I did not believe there was a serious threat. I was up there in a plane for an hour or so and looked at some maps and studied that area, and I didn't see any big threat. So, it would be unreasonable of me to suggest that the public should have understood it when I was privileged to be

briefed by the real experts and I didn't see any big threat at that time. So, I think that in future situations like that, we have to expect that a certain amount of confusion will certainly exist, particularly at the local level and among the general public.

I will review briefly the history of federal disaster relief and then try to tie this into the Mount St. Helens experience.

HISTORY OF FEDERAL DISASTER RELIEF

By way of background, we have had a permanent federal disaster relief program since 1950. Prior to that time, we had a number of special Acts to address special situations like the 1906 disaster in San Francisco and so on. But, in 1950, for the first time, we got into the disaster relief business on a permanent basis. From 1950 to 1970, we only concerned ourselves with the restoration of public facilities, and public facilities we define as roads, streets, bridges, libraries, city halls, and so on. We never concerned ourselves with the problems of individuals. We got into that business following Hurricane Camille in 1969. We had an Act in 1970 that for the first time put the federal government in the business of providing assistance to private citizens. Prior to that, it had always been handled exclusively by the private sector, volunteer relief organizations, and so on. There were a number of changes in law, which I won't go into, between 1950 and 1970. We had a new law in 1974 following Hurricane Agnes, and it is the current law. It's had some minor changes, but not very much.

FEMA'S ROLE AT MOUNT ST. HELENS

In response to previous questions, I would like to state that FEMA does have a role in non-declared disasters assigned by a Presidential Executive Order, and the question of when this ought to be invoked is one that is very much up in the air. It has not been answered and was not answered at Mount St. Helens.

I want to discuss the 75% federal share of the cost of rebuilding in public declared disasters that Mayor Edmondson referred to. That is the federal policy. It was at Mount St. Helens and continues to this date. I can assure you that it was federal policy because I personally posed that question to President Carter on the tenth of June in Seattle, and I can remember distinctly what the President said to me. He said, "Bob, I want you to hang tough on that issue." That's the federal policy. That policy does not address where the other 25% comes from. It merely says that, of the eligible disaster relief for public agencies, government agencies at the state and local levels, federal participation will be limited to 75%. The other 25% can come from the state or it can come from other sources or from local government.

Incidentally, we did have a declared disaster in Idaho as a result of the same eruption, and Governor Evans in Idaho set up a simple formula where the state paid 15% of the eligible cost, FEMA, through the President's disaster relief fund, paid 75%, and local governments paid the other 10%. That, obviously, does cause some problems for local governments, but, at least, it was a simple system, and the state did participate. In the state of Washington, the state did not participate to that extent.

So, typically, when we get a major disaster or an incident which involves federal assistance, that's when our agency gets directly involved. It's usually a pretty big one. It varies from year-to-year, but, typically, over the last ten or fifteen years, we have about 50 of these a year throughout the 50 states and the territories. Under the normal situation, of course, it has to be something that is beyond the capacity of state and local governments to handle.

The law specifically requires that the Governor make a request to the President. That is a statutory requirement which we honor in every case. We do require a letter from the Governor, signed by the Governor, addressed to the President, requesting disaster relief. The law requires that the request be made in order for the President to exercise his discretionary authority to declare a major disaster. Administratively, the Governor's request is handled by the regional FEMA office. There, we do some administrative things with it, make an

assessment and a recommendation, and so on. Administratively, it goes from the Governor's office, through the regional FEMA office, to the director of FEMA, who in turn takes it to the President.

In the case of Mount St. Helens, we did not get our declaration of a major disaster until May 21. There is a very basic reason why it took that long; we did not get a request from the Governor of Washington state. Because the pressure was building so much through other political channels, i.e., the Congress, and so on, a decision was made to bring the President to the site, and, in effect, force the issue. As you know, the President was there on the 21st.

I mentioned that the President makes the determination. I was the Regional Director for a little over 11 years, in that business under four different Presidents, and in every instance to my knowledge, the President made the decision personally. I would get back from the White House an original document with the Presidential signature on it approving a major disaster, so it is not taken lightly at that level.

The law requires the President to appoint a Federal Coordinating Officer. The duties of a Federal Coordinating Officer are something I'm going to talk a little more about later on; that was my role at Mount St. Helens. I did not know until late on the night of the 20th that I was to go to Mount St. Helens. About ten o'clock that night, I got a telephone call advising me that I was going to be assigned to Mount St. Helens. I was in San Francisco, and, of course, Washington state is not my region. I didn't know until ten o'clock the next morning that I was supposed to brief the President that afternoon.

The Federal Coordinating Officer's responsiblity is to coordinate federal disaster relief. He also has the responsibility to administer the President's disaster relief fund, and this is the direct federal assistance, 75-25, that Mayor Edmondson talked about earlier. He also has the responsibility for setting up field offices and disaster assistance centers and so on. Once you get a major declaration, there are certain kinds of emergency things that are authorized under federal law. There are also emergency actions that are authorized by other federal agencies under other federal laws, but we don't have time to get into that here.

Under the Disaster Relief Act, there are certain basic kinds of things that can be done. We can provide search and rescue, and the question of using military resources always comes up. It was a very hot issue at Mount St. Helens.

One of the disadvantages of having high-level political officers show up on the scene is the expectations that people get as a result of their having been there. Both the Secretary of the Interior and the Secretary of the Army were with the President that night, and the next day people's understanding of what that meant was, in some cases, very different from reality. We can provide support for search and rescue, including the use of military. But the military is a last resort for several reasons. First, it is very, very expensive. People seem to have the impression that for some reason the Department of Defense operates as a "freebie." Let me assure you that that's not the case. You might sometime take a look at that chunk of the budget, and you will understand. When you start paying the out-of-pocket costs (as I have done a number of times) of military involvement, you find that they are very, very expensive. It can not be used when state or commercial resources are available. That caused a great deal of misunderstanding at Mount St. Helens, one of the state resources obviously being the National Guard. The National Guard has tremendous capacities. In Washington State, they were grossly under-utilized.

We can provide things like mass care and feeding. We do that also as kind of a last resort. Under the normal circumstances, the American Red Cross and other volunteer organizations fulfill that responsibility very, very well. We expect them to do that, and we don't get involved unless they get into trouble. Sometimes we provide resources to organizations like the Red Cross to do those kinds of things. We can provide medical supplies or medical assistance. If my memory serves me, we actually provided about

700,000 surgical masks up in Washington state. The first 300,000 from Department of Defense resources, and the second 400,000, we got out of the commercial market. We went out and bought them and had them flown in and turned over to the state.

The types of major disaster programs that are available for people under the Disaster Relief Act include temporary housing. At Mount St. Helens, we actually provided housing to 300 families. There is an individual family grant program which is a state-administered program, federally funded, which provided about a half million dollars to families that had no other resources, no other way to respond to this thing. About 400 families got a half million dollars. We did fund some crisis counseling activities. The Small Business Administration and the Farmers Home Administration made available a number of low-interest loans to farmers and to businesses. The Mayor also touched on that. That program was not nearly as extensive as it was first expected to be.

One of the very real problems, and I think the Mayor covered this quite well, was the over-statement of the problem. Early on, the cost estimates that were coming in were just totally unreasonable, and, as a result, there was some kind of odd reaction to it. For example, the tourist industry dropped off. Everybody away from thought the whole state was out of business. At the height of the salmon fishing season, for example, over on the coast, during the time when sports fishing boats would be operating at full capacity, less than half the boats were actually going out and they were going out half full. So they were going out something under 25% of what was their normal. This was because of the public's perception of the magnitude of the problem. However, that area over on the west coast of Washington was not physically damaged at all.

A couple of other things: We paid some disaster unemployment claims for about 3,400 loggers or so who were unemployed. A couple of state agencies, I thought, did an outstanding job and were ready, willing, and available to do it. The State Insurance Commissioner's Office, I thought, did an outstanding job. They got the insurance people together. A comment was made yesterday about the coverage of private property under commercial insurance, and the insurance companies did pay off on a lot of the automobile claims under the comprehensive provision, and although they were not successful at getting a policy instituted across the board in the insurance industry, they did get a good response from the insurance industry. I think the State Insurance Commissioner's Office deserves credit for that. The other agency in the state that I was impressed with was the National Guard. The National Guard's inability to operate effectively was not their fault. They required an order from above, and that order was withheld. They were available and willing to do the job. General George Cotes, up there, told me on several occasions that he had the resources to do the job if they had simply let him do it; but the orders were not forthcoming. I think it is appropriate to mention that, in my experience, the National Guard, when they are permitted to function, function very well.

There were also some comments made about the Department of Emergency Services in the state. Maybe it is a little parochial on my part, but that was kind of unique in Washington state; the individual who was the Director was new to the job, as was previously pointed out, and he was somewhat hamstrung with resources. That would not be the case in California. You have a very different organization in California, and, in today's climate in California, the types of problems that occurred up there would simply not occur in this state. I want to make that point.

The other federal agencies that do have a very significant role in disaster relief are the United States Army Corps of Engineers. They did a tremendous job of clearing the channel in the Colombia river. They took out about 44 million cubic yards of material out of the Colombia river and did restore shipping in something like three and one-half weeks. Incidentally, they just completed a study of what needs to be done in the Cowlitz and the Colombia river systems in the next few years, and they are

estimating that there will be something on the order of 400 million cubic yards of material deposited annually off the mountain.

The Small Business Administration and the Farmers Home Administration made low-interest 30-year loans. Incidentally, the law has been changed since then. At that time, they were making three- and five-percent loans, and it is now much, much more costly than that. The Federal Highway Administration, of course, on Federal Aid System roads, the Department of Health and Welfare, and the Department of Education, all were involved in the emergency.

On the following pages are some photographs that touch on how we performed at Mount St. Helens.

DISCUSSION

Question: Is it possible to get an unbiased description of what the problems were at the state level in Washington?

Stevens: The election following the Mount St. Helens eruptions was the first time in 76 years that a sitting Governor failed to survive her own party's primary for re-election, so the general public in Washington, apparently, felt pretty biased about Governor Ray. She was attempting, very candidly, to avoid spending any money, even though I and others repeatedly attempted to explain to her that that was not the "name-of-the-game." Federal disaster relief is by federal law supplemental to state and local effort, and we had a contract with her which provided for reimbursement at the 75% rate, as I have indicated. A good example, now that I am retired out of the system (I think I can be fairly candid about this), was the use of the National Guard. I was getting requests which contained the certification by a senior state official that it was beyond the capacity of the state of Washington to provide search-and-rescue aircraft. At the same time, a leading general in the National Guard was telling me that he could easily do it if they would just permit it.

Question: How did the Mount St. Helens cost, out of the President's disaster relief fund, compare with some of the other big disasters?

Stevens: It was actually less. In the flood and mudslide disasters in southern California in February 1980 we spent 615 million, considerably more that is, in the Los Angeles Basin Area and several adjoining counties than we spent out of the President's Disaster Relief Fund at Mount St. Helens. There was an incumbent candidate for the United State Senate in Washington state who was campaigning by making announcements that he had obtained an appropriation of $942,000,000 for federal agencies for Mount St. Helens. That's true. There was an appropriation of $942,000,000, but it was not restricted to Washington state, and in most cases -- a couple of exceptions being the Forest Service and, I think the USGS, but in terms of dollars, those were very small amounts relatively. In all of the rest of the cases, that appropriation was actually two funds. At that time, I was Regional Director of FEMA in San Francisco, and I spent more money out on that appropriation in southern California, for example, than went into the state of Washington.

Incidentally, disaster relier funding has always been a very difficult problem at the federal level because you simply can't plan for these kinds of events. We have had a long, long standing agreement with the committees of the Congress that we would ask for small initial appropriations, and that we would then go back for supplemental requests as required. That worked very fine for many years until suddenly the cost of federal disaster relief began to get a little out-of-hand, and there began a great deal of concern, and this started during the immediate past administration -- not the current administration. A good bit of concern about the amounts of money that we are spending, and for the first time in all those years, we have failed to get a supplemental appropriation without delay out of the Congress. We had a big disaster in southern California in March 1980, and I had a lot of other project applications, eligible work, in my office that I couldn't fund, because we

didn't have the appropriations. After we got through Mount St. Helens, we went back and funded all of those, of course, but, times were getting tough then, and they are getting considerably tougher now. The Corps of Engineers estimate they need seventy million dollars for dredging and mudflow alleviation work during the current fiscal year up there. They are not likely to get it and it doesn't look very encouraging. To have the authority to do it is one thing; but it must be funded as well, and funding is becoming more and more of a problem all the time.

Question: What percentage of requests for federal disaster designations are turned down at the White House?

Stevens: It is about a third. For every two approved, about one gets turned down. Alex and I have had some rather extended discussions about that in California, which has been turned down occasionally. The President declares about 40 to 50 projects a year, and during recent years (prior to 1980), the total cost was running about a billion dollars a year.

Figure 1. This was a presentation to President Carter during his first visit on May 21. Rocky Crandell of the USGS conducted geologic hazard investigations of the volcano and explained the hazards here. Rock, along with Don Mullineaux, wrote the 1978 Volcanic Hazards Report, and they received a great deal of credit.

Figure 2. The National Guard was in camp. They had gone to camp at the Yakima firing range the day before the 18th. They reported for their two weeks of summer training on the 17th, and they were in briefing at the time the mountain erupted. They got all except one of their helicopters out. The first two weeks of the emergency, they were actually on Federal duty and were effectively utilized. When those two weeks were up, and they went off Federal active duty, the state started to incur some costs of using the Guard, causing political pressures to build up. But, they were on active duty those first two weeks and were used extensively.

Figure 3. This scene was in Yakima. One of the big problems mentioned is the cleaning of the streets and the disposal of this debris. Incidentally, on this particular date, I inventoried the Federal resources for street sweepers. One of the very critical problems was the availability of street sweepers. In the United States Department of Defense, there were only two self-propelled street sweepers in the Pacific Northwest, at least on the 25th of May. One of those was at McCord Air Force Base in Washington state, and the other one was in Mountain Home, Idaho, and it would have taken an Act of God to get either one of those off those bases because of their war-related missions. We simply do not have a reserve of these kinds of resources available to the cities.

Figure 4. This photo shows where the actual mud line formed on that house as it was moving down the north Toutle drainage. This is right after the eruption. I'd seen a lot of floods and a lot of flood damage, but I'd never seen one where the mud got clear up on the roof of the house.

Figure 5. This is our operation within FEMA itself. This is after May 21 when we set up a centralized public information activity. We used the Federal Public Information Officers from about nine different agencies. We had one from the state. We tried to get more state participation, without success. The Governor really felt that our FEMA field office should have been in Olympia rather than in Vancouver. But this location was very convenient and successful. We conducted the briefings here for all the Federal activities. One of the things I insisted on was that all the Federal agencies participate and release their information through here, and they did, and after the first day or two of getting underway, it worked very well. The Forest Service, of course, was a principal participant, as was the USGS.

Figure 6. This is Tim Haight, USGS geologist turned public relations man for this event. I've never asked Tim if the USGS runs a charm school, but I can tell you that this guy was a real hit with the media.

Figure 7. We used a computer in Vancouver so we could do our direct mail through an outlet in Portland. One of these little Apple computers that you hear advertised. We could put out 3,000 direct-mail pieces of advertising in about an hour and one-half in the middle of the night, and we did, --- many, many nights.

Figure 8. Dr. Dixy Lee Ray, then Governor of Washington. This was part of her public information activity during a press conference one night.

Figure 9. We set up a disaster hotline, and I would recommend that this be done routinely in major disaster situations. We published this photo and sent it to TV stations in Idaho, Washington, and in the adjoining areas of Oregon. The TV stations in Spokane got us coverage in northern Idaho. We manned toll-free lines 24 hours a day initially, and we tried to respond to all questions from the general public. It's tremendous!

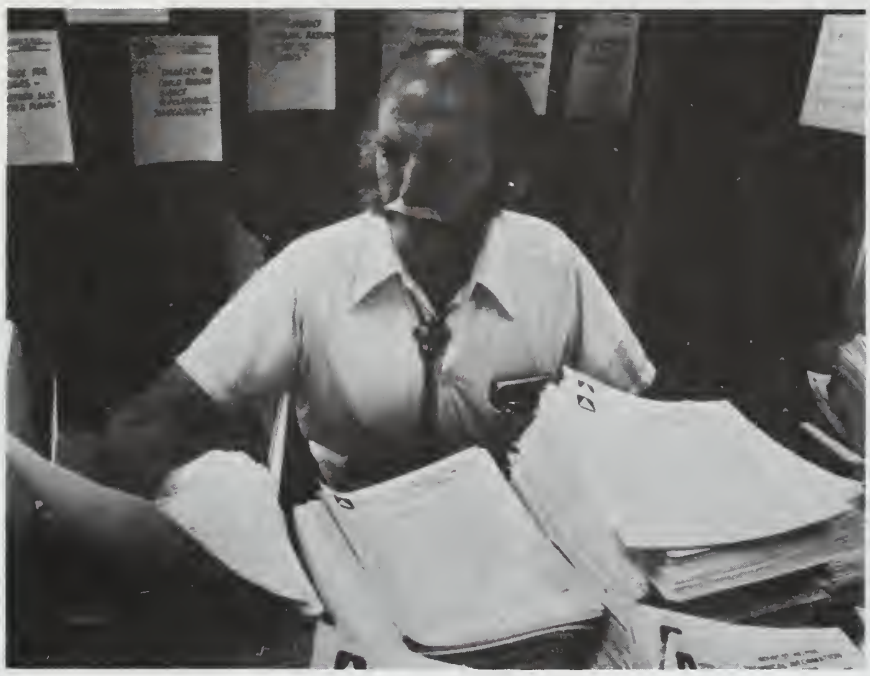


Figure 10. We published a technical information bulletin up there. This came about as a result of a comment that the President made during his May 21 visit. We published 34 of these out of our office on our letterhead. They covered all subjects, a great deal of information from USGS, and from the Center of Disease Control. That is another Federal agency that got very little recognition, but that played a very major role up there. We had physicians out of Atlanta, and they were undertaking research projects. We were able to put out public updates on this.

Figure 11. This shows one of our disaster assistance centers. We had, I think, a total of about ten different locations throughout Washington and another three or four in Idaho. The purpose of the disaster assistance centers is to bring together in one location all of the government agencies and, hopefully, all of the private relief activities that are available for citizens. Then you advertise this extensively, and, if necessary, set up a mode of transportation to get people into the center and it will provide the whole array of assistance available in one location to the general public. This is a cooperative effort between the state and counties and communities involved. The American National Red Cross is almost always at the disaster assistance center. There are other private relief organizations that also participate, but the coverage of the Red Cross is more extensive than any of the others.

Figure 12. This was President Carter's second visit, and in my experience, this was the first time we had ever had a President visit a disaster area twice. He returned on the tenth of June because of a previously arranged commitment to address the Mayor's Association up in Seattle. He asked that we come up and meet with him, and we were supposed to have thirty minutes of his time that morning. We actually had about forty minutes with him in a private session with no press questions, except that the press was admitted to take pictures. One of the problems that someone in my position is always faced with is who do you take to this kind of session because you must keep it very small. I tried to take the people who had made a significant contribution to the Federal effort, and the people were Dr. Bob Bernsetin, on the left from the Center for Disease Control; Don Mullineaux, USGS, next to him; myself; and the President. The next fellow is Roger Slegeizen, who, as Deputy Director of OMB, was very concerned about the money we were spending. Next is General Dick Wells from the Corps of Engineers and Bob Takarczyk from the U. S. Forest Service. Those were the Federal agencies who I felt deserved an opportunity to meet and talk personally with the President. The other fellow in the picture is Jack Watson, Chief of Staff at the White House.

ROLE OF THE CALIFORNIA OFFICE OF EMERGENCY SERVICES IN NATURAL DISASTERS

Alex R. Cunningham, Director
Office of Emergency Services
Sacramento, California

ABSTRACT

Whatever the type of disaster, the Office of Emergency Services must be ready to assist local government in preparing for and responding to the crisis. At the same time, despite the amount of support that state, federal, or private sector organizations provide during a crisis, it is the affected city or county that always remains in control of the response effort.

Because most of California's volcanic areas are remote from major cities, relatively few resources would be closely available for emergency response. Transportation, hydrologic, and power facilities would therefore be impacted by a major eruption as much as moderate sized population centers. Because of the remoteness of the potential disaster areas, transportation and communication lines would also be severely taxed.

With emergency resources not readily available in these areas, we anticipate that state, federal, and private sector resources will be in immediate demand following such a crisis. Acting as the direction and control arm for the Governor, the Office of Emergency Services (OES) will work with other local, state, federal, and private sector organizations to provide the support needed. In providing evacuation support, for example, OES might coordinate with local law enforcement groups, the California Highway Patrol, and Caltrans to get the necessary manpower to the area. The California Department of Forestry, the U.S. Forest Service, and local fire districts would be available to provide firefighting assistance. Search and rescue support would be provided through private sector resources, the National Guard, or the California Highway Patrol. The National Guard would also play an important role in air-lifting manpower and equipment into the disaster site.

Finally, OES would assist the affected area by working with local officials to aid them in qualifying for disaster relief funds.

RISKS OF NATURAL DISASTERS

There's no question in anybody's mind that natural disasters, particularly in California, are a way of life. They are going to occur even though they don't occur with great frequency, which is both fortunate and unfortunate. The fortunate part is that the victims are kept to a minimum and people are inconvenienced less than if disasters occurred with the frequency of, say, a neighborhood fire. It is unfortunate in that because disasters don't occur with great frequency, people tend to forget or be unconcerned with their likelihood. At all levels of government, in fact, there is not as much being done in the way of preparedness as should be done. And we at the Office of Emergency Services are constantly trying to get people more interested, and trying to bring in the private sector for mutually beneficial assistance in emergency preparedness.

One of our problems is related to the formula that we use in disasters, which is that risk equals probability times the consequences. Now if the probabilities are low,

even though the consequences may be great, the risk is perceived to be low, and vice versa. If it is something for which the probability of occurrence is quite frequent but the consequences are not great, the risk is not considered to be great. We see that there is much done towards preparation immediately after a disaster such as the wildland fires of 1970 and 1981 in California. When something like that happens (with very high probability and almost predictable consequences), we have no problem at either the local level or the state level in getting monies for fire-type programs.

People who live in earthquake-prone areas don't take them seriously until the earthquakes occur. Then when a major earthquake does strike, as it did for example in southern California in 1971, the newspapers are flooded for days and days with all of the types of thing people should be doing. If no earthquakes strike for the next month or two, we don't see such things appearing in the paper. This conference is a good example. If we had held this conference two years ago today, we would have had the State Legislature saying, with good cause, "Hey, you guys are wasting money. We're not going to have any volcanic eruption." And local government would have said the same thing. However, because Mount St. Helens did erupt, we met with local governments and held a volcanic hazards workshop seminar at Mount Shasta City this year which was extremely successful. The counties and the cities had the right people there: the sheriffs, the police chiefs, the emergency services fire coordinators, the medical people, the transportation representatives and public works people. There was a tremendous amount of enthusiasm because a disaster in a nearby state did actually occur.

There has been comment today about the emergency services organization in the State of Washington which, as Bob Stevens of FEMA said, are structured differently than we are at OES. We think we would be much better prepared than they were because their leader had only been on board for six weeks before the disaster occurred. There were also some other factors which I will discuss further a little later. Sheriff Nelson, however, did mention that one of the biggest problems Washington State encountered was that there was no formal mutual aid structure; mutual aid is the foundation for the emergency services program in California. It is a time-tested system that has worked very well. Will it work in the big disasters? The major earthquakes? The 8.3 Richter magnitude that everybody says is coming? We think it will, but there is still room for a little fine-tuning.

PURPOSES AND OPERATIONS OF OES

First, I'd like to give you a brief description of our goals and an overview of how we are set up in California.

Although the primary goal of the California Office of Emergency Services is one of coordination and support, this office serves as the directional control arm of the Governor's office in all state responses to any major disaster. We work with federal, state, and local agencies to insure that efforts at all levels properly mesh. We assist state agencies and local governments in developing emergency plans, contingency plans, and standard operating procedures to cope with the multiplicity of disasters which we in California must face. We work with communities in areas adjacent to nuclear power plant sites developing off-site evacuation plans and conducting exercises to test these plans. And, we maintain the California Emergency Plan, the bible of laws, rules, and regulations by which we and local governments work. We conduct training courses and assist local jurisdictions in their training efforts. We also assist in hospital exercises required as part of the hospital certification program. And, in times of disaster, we coordinate the movement of mutual aid supplies, materials, and manpower to respond to the needs of the stricken community.

To accomplish this task, the state is divided into six mutual aid regions. Mutual aid coordinating centers are located in Los Angeles, Concord, Redding, Fresno, and San Bernardino. Mutual aid is a program whereby neighboring local government helps a

disaster-stricken neighbor. This is accomplished on a voluntary level during local emergencies and becomes mandatory upon a gubernatorial proclamation of a state of emergency. In addition to the resources available from other state agencies and local governments, the California Office of Emergency Services has resources which may also be used. We have 25 miles of quick-coupling pipe to move water from the source to a fire or to serve as the water supply line for a stricken community which has lost its water supply to a flood. We have approximately 100 pumpers strategically placed with local fire departments around the state. These pumpers may be used by these departments in their daily operations for second alarm fires or greater, with the provision that if needed for mutual aid they will be dispatched with crews to the area of need. Eighty-five of these pumpers were dispatched to San Bernardino in November of 1980.

OES is currently testing a dual-purpose, heavy-rescue fire fighting unit, designed and built by OES. Along with usual fire fighting equipment found in most fire units, this vehicle has heavy rescue capabilities. It has, for example, rescue equipment such as a Hurst tool used to pry apart metal and hydraulic shears used to cut through up to 3/4 inch bar. These tools can be used to free a trapped victim from a truck or a car. Other rescue equipment includes this air bag system. Each air bag can lift up to 12,000 pounds on locations where mechanical equipment cannot be used.

We have also developed this monster which carries two huge portable pumps with 5,000 feet of 5 inch hose and 7,000 feet of 2 1/2 inch hose.

No disaster response effort can function without adequate telecommunications. OES developed and today manages the California Law Enforcement Mutual Aid Radio system, or CLEMARS, with over 6,000 mobiles, portables, and base stations loaned to local agencies and licenced on the system. We encourage participation in a similar program for fire services, the Fire MARS program. We also utilize unique equipment such as this unit which can function on any one of 9,000 channels and mobile communications vans or trailers to support fire operations capable of operating on all major frequencies used by fire departments, the U.S. Forest Service, the California Department of Forestry, and the Office of Emergency Services. We also maintain communications vans to support law enforcement agencies, capable of communicating on frequencies of the California Highway Patrol, CLEMARS, Fire MARS, and our own command and control system.

At major disasters involving multiple agencies, we have developed mobile command complexes, providing a 35-foot trailer for communications, a trailer for operations, and a trailer where command decisions can be made.

The California Warning Center is located in the California Office of Emergency Services' headquarters complex in Sacramento. This facility is staffed around the clock and provides the capability to communicate via hot-line throughout the state as well as the nation, using the National Warning System. And we access existing teletype networks throughout the state and the nation to provide and to obtain hard-copy messages.

We have experienced many major disasters in California, some more unique than others -- such as, for example, the 1,000-year flood that hit northern California in 1964. The devastating flood waters in the valleys of the Eel River were sometimes 37 feet above the road bed.

We have seen major fires burn valuable watershed and destroy homes and businesses. In 1977, 234 homes were turned to ashes in Santa Barbara and 39 additional were damaged. In 1978, the toll of the Malibu-Agoura fires was three killed, 53 injured, 258 homes destroyed, 45 others seriously damaged, 13 businesses burned, and 37,700 acres sorched. In 1980, 385 homes were destroyed and 451 damaged as fires whipped by winds in excess of 100 miles per hour raced through the City of San Bernardino and portions of Los Angeles.

The Roseville explosions of 1973 began with a smouldering fire in one of 22 boxcars containing bombs destined for the Pacific Far East. Damage to the areas adjacent to

the yards was estimated at 3.7 million dollars. Pending lawsuits were in excess of 400 million dollars.

In 1980, in addition to 215 earthquake investigations, 131 severe weather accidents, 51 flash-flood advisories, 26 major fire incidents, 239 river bulletins, and two tsunami incidents handled by the California Warning Center, we also coordinated responses to oil and hazardous materials spills. The total for calendar year 1980 was 624 oil spills and 243 radiological or chemical spills.

We at the California Office of Emergency Services also coordinate all search and rescue services within the state where mutual aid assistance is required. During 1980, this total amounted to 319 incidents.

The most frightening of all disasters is the earthquake. On February 9, 1971, an earthquake jarred San Fernando, California causing millions of dollars of damages. Yet the 6.4 magnitude earthquake was small by comparison to the 8.3 magnitude earthquake which hit San Francisco in 1906 or the 8.3 magnitude earthquake expected to occur somewhere in California -- for California is indeed earthquake country.

Disasters are big business. From June 30, 1962, to June 30, 1981, the California Office of Emergency Services processed claims from local governments for federal funding assistance in excess of $367 million. With the numbers, types, and magnitudes of the disasters which we have experienced in California in the past and those which we may experience in the future, we have no choice but to be prepared.

LEARNING FROM THE MOUNT ST. HELENS EXPERIENCE

Mayor Edmondson of Yakima mentioned this morning that one major problem during the eruption was that the ash fall from Mount St. Helens occurred at about 9:00 o'clock on Sunday morning when the Department of Emergency Services was closed. We wouldn't have that same problem in California since we have a 24-hour operation system. Now, as a result of Mount St. Helens, the State of Washington Department of Emergency Services does have a 24-hour operation and communication system.

Another helpful feature of our system is that much of the equipment is not actually operated by the state. It is owned by OES, but it is placed in the hands of local government. It is maintained and used by local agencies who would have first-hand information about a disaster in their area. And, since we own the system, we can loan it to any jurisdiction in the state.

Why do I think California is in a better position to respond to a major disaster? I'll go to a short story that Avril Hariman once told. He was asked why he was the world's leading diplomat and he said, "It's because I make consistently good decisions." The interviewer went on to ask him, "What is it that enables you to make consistently good decisions?" And he said, "Experience." And he was asked, "How did you obtain that experience?" He answered, "By making bad decisions." Well, I think its the experience factor that has allowed California to be looked upon as one of the emergency preparedness leaders in the nation. We have handled 787 earthquake investigations, 406 severe weather situations, 105 flood advisories, 2,688 oil spills, 1,273 search and rescue missions, 136 major fires, 903 radiological and chemical responses, 15 U-2 over-flights, 230 NORAD fire reports, 35 mud slides, 4 train derailments, 42 bomb threats and disposals, and about a thousand miscellaneous mishaps.

Why do I point that out? I'm trying to relate to the point made earlier about not creating a special system to handle each and every type of disaster. Many of our speakers this morning have said, "What we really need to do is to develop a system that is flexible enough to handle all types of disasters with simple modifications." That's what we in California have striven to attain. Obviously the foundation for us is the mutual aid system. The important thing is that local governments must know how to access that system in order to obtain the resources.

Sheriff Nelson asked, "Who is in charge in a disaster?" It is a question that always arises. In California, where local government is autonomous and self sufficient, we support the concept that local government must always remain in charge of managing a disaster. The state is available to support local government and to be the single point of contact that they can use when they need state resources or federal resources. Our mission is to support local government.

We have three people in our law enforcement division who serve as law enforcement coordinators. The sheriff from Washington mentioned today that during the eruption he needed additional law enforcement support and had to phone old friends because there was not a formal mutual aid system. We do have such a system and we were able to use it just recently in the Diablo Canyon situation. We have fire coordinators and communications coordinators who are planners and organizers, but they do not go in and take over when the disasters occur.

When a disaster occurs, we are responsible for pulling the strings so that local government doesn't have to worry about "who do I contact if I need this or that kind of assistance." They contact one organization, and that's us.

The real heroes in the disaster are those on the scene: The CHP (the highway patrol), the National Guard, the California Conservation Corps, the Department of Water Resources, all these agencies. But somebody has to pull it all together. Ultimately when we run out of resources we have to go to one place and that's the Federal Emergency Management Agency. That's the way the system works.

With respect to the private sector, we have something called Plan Bulldozer, which we put together with the Associated General Contractors and the Grading and Contractors Associations. This plan has predesignated the rates for different types of equipment and has made the overtime arrangements. When we need the equipment -- for example, eight D-8 cats -- we simply go to them; we don't have to own or maintain them. We have a similar agreement with the Structural Engineers Association and the Building Inspectors, so that if a disaster hits they will give us the right people to assist. We'll arrange the transportation and get them into the area to assist local government.

What is the mechanism under which we operate? In California, we have something called the Emergency Services Act, which was passed by the legislature in 1971 and has been copied by many states. In the Emergency Services Act is a Governor's administrative executive order which charges me with the responsibility of meeting with all the various state department directors, determining how they will respond to major disasters, and tasking each of them for preparing detailed plans. Our plans must be general in nature; theirs must be more specific. These administrative orders have been carried out with all of the state agencies in California.

Now, how do you test the system? You test it one of two ways. Either during the actual disaster, as they did at Mount St. Helens, or by holding training, tests, and exercises such as the conference that we're having here today and the workshops conducted at Mount Shasta City last month. I have with me just some of the things that came out of that conference: a search and rescue annex, a fire annex, a public works annex, a communications and warning annex, a law enforcement and an emergency medical annex. These are problems they identified and specifically addressed -- those things that they would have to do in responding to an eruption.

As for my planning philosophy, I think plans in and of themselves aren't worth the paper they are printed on, but the analysis that went into the development of that plan, the fact that we brought the right mix of people together to identify who can do what for us in time of disaster, is what's going to save our bacon.

At the Mount Shasta conference, for example, we had six counties from California plus two Oregon counties, and seven cities involved. The reports that we got back were extremely encouraging.

Now, major problems: If a Mount St. Helens type of disaster occurred at Mount Shasta, about 12,000 people would be immediately affected. There would be some major problems such as evacuating people from remote areas where only limited transportation resources are available. In the area, the roads are not wide and there are very few airports. Another concern: how will we communicate actions that the public needs to take in an area with limited media resources? Gilbert White last night said that one of the difficulties is how to communicate the information into the various organizations in a useful format so that proper actions can result. We also have to look at meeting the needs of the people affected by the disaster, such as shelter, food, clothing, unemployment, relocation.

What would be our role in responding to the volcanic eruption? First of all, we must be ready to assist in the area with whatever support is needed. In an area of limited resources like Mount Shasta we think state assistance is going to be absolutely crucial. Again, they need to know how to access the system. We would call on the California Highway Patrol, the State Department of Transportation, the California National Guard, and local law enforcement agencies, because we work this whole system of mutual aid from the bottom up -- neighbor helping neighbor. If necessary, if the disaster is large enough, we will set up a disaster support area adjacent to the impact area and bring in emergency resources from all over the state and, in fact, all over the country.

If necessary, and it almost always is, an emergency public information center should be set up in order to deal with the media demand for information. That was one of the biggest problems they had at Three Mile Island. Everybody was saying something different and there was no coordinated center. We have had, for years, an emergency public information center and it has been employed before in some large disasters. We see that being streamlined by some of the things that are happening on the Governor's Earthquake Task Force. We need to be able to upgrade the communication systems in order to get the necessary information to the public. We saw the Mount St. Helens disaster as a valuable learning experience, and we sent our regional manager from the Redding area, who had both Mount Shasta and Mount Lassen in his region, up to Washington State to assist. Along with three communications coordinators, he provided some very needed assistance. We did this because of the interstate mutual aid agreement we have with the State of Washington, which had some real communications problems since they are separated by mountain ranges. We were able to send up three suitcase portables that tied in with the ATSV3 satellite and provided them the necessary communications links. They operated the system and we provided the technical expertise with the resources that we had available. We also offered our command and communications vans, and our law enforcement vans to Washington, and they did not take us up on one of the law vans. It gave us the opportunity to reexamine our plans, our general plans, and led to holding some planning sessions and workshops in local areas.

Now obviously government can't do it all. We think that in a disaster of this type we're going to be lucky if we can get major amounts of resources in there in the first 6 to 12 hours, just simply because of the distance involved. For an earthquake, we're looking at probably 24 to 48 hours. What's the key? The key is better preparedness at the local government level, better involvement by the private sector, and individual preparedness. People have to get back to the basics of taking care of themselves in the wee small hours following a disaster. In California, the phone company has put a survival guide in the front of every telephone book with information provided by the California Medical Association, the Seismic Safety Commission, the Red Cross, and the Office of Emergency Services. Finally, we've got to get all levels of government to look seriously at disaster preparedness. The leaders must get involved. As the mayor said earlier today, leaders can't forget the fact that disasters can occur in their areas. They need to assign responsibilities to the local department heads and they have to actively participate in exercises, because when the disaster occurs, they will be the ones who will have to take charge. We put on exercises with local government all over

the state so that in the end we will be better prepared. They must also provide sufficient staff; not just one person designated as the emergency response coordinator as many local governments have done.

In Washington State, they did have their problems. They had a new leader aboard; they also had a legislature that had cut their staff of 60 down to 22 in two years prior to that disaster. Why? Because disasters don't occur that frequently. State legislatures and local governments have some real hard decisions to make. This is true in California right now because of the shortage of funds. We are asking for some dollars to prepare for something that may never happen in the case of the great earthquake. But it may happen, and it could happen tomorrow. So governments have a tough decision because they have now problems such as at the local level where street lights are requested at a certain intersection where they've had some fatalities. They need to upgrade their school systems, and here comes somebody asking for $10,000 to bring on one more emergency planner to prepare a volcano plan. But we do have to keep trying to improve the system, because the next disaster is always just around the corner.

Finally, in closing, there are always many people, including the news media, who are quick to tell you how to do your job or what you did wrong after the disaster has occurred.

DISCUSSION

Question: Do you have a volcanic hazards plan in the State of California?

Cunningham: Our plans are generic in nature. We do have a general evaluation plan that, again, assigns certain responsibilities to certain state agencies. From our level, it doesn't matter if you're evacuating people for a flood that is coming, for a dam that's going to fail, such as the evacuation of some 80,000 people below the Van Norman Dam after the earthquake of 1971, or for a volcano. The people that have to have the specific plans, in this case, would be for traffic control and law enforcement, such as the sheriff of the county. He has to decide about road blocks, congregate care centers, and so forth. But our role there would be to send him law enforcement officers and then they respond to him. We work with local governments to give them these specific plans.

Jim Davis: At the National Earthquake Evaluation Committee meeting in Golden, Colorado where the Peruvian earthquake prediction was being evaluated in January, there was a science representative from the Peruvian government who stood up after the scientists who had made the prediction had given their presentation and before there was a caucus to consider the implications of this prediction. He said to the committee chairman, "Mr. Chairman, if you validate that prediction, would you please advise us whether to evacuate Lima to the north or to the south?" So, I would like to point out to the OES that we do have to take the direction of evacuation into account, depending on what the hazard is, and we all have to keep the dialogue going or we're going to be doing the wrong thing at the wrong time.

Also, my earth science colleagues should note that we do hear the people we work with in the policy areas, such as Alex, more generally speak of when the big earthquake occurs, rather than if, and this is important. We have more problematic considerations when we're talking about specifics in individual volcanic cones, as we learned yesterday.

THE CALIFORNIA STATE GOVERNMENT'S ROLE IN NATURAL HAZARD EMERGENCIES: A LEGISLATIVE PERSPECTIVE

Joe Lang, Consultant
Commission on Government
Organization, California State Assembly
Sacramento, California

SUMMARY

Effective emergency management requires a high degree of priority from top level policy makers as well as coordination and planning. For the last several years, the California State Legislature has been critical of California's emergency preparedness system and our overall level of preparedness.

Recent initiatives, however, on the part of the administration have made some improvements in our preparedness system. These include creation of the Emergency Task Force on Earthquakes, the Southern California Earthquake Preparedness Project, and others.

While those initiatives have made some gains, California still has a long way to go to become adequately prepared for a major hazard emergency.

VIEW FROM THE LEGISLATURE

I would like to discuss and offer some advice as to how the subject of preparedness and the science of geology fit together from a legislative perspective. One of the important but unfortunate things to understand is that the Legislature, in the past decade or so, has become a very reactive body. By that I mean that, generally, we tend to react to problems after they happen. We tend to react to proposals that the administration gives us rather than playing a lead role in trying to deal with problems ahead of time. Fortunately, I think in the case of Emergency Preparedness that is beginning to change. For a lot of very good reasons, the Legislature is paying more and more attention to the question of preparing our citizens to respond to major types of disasters, such as earthquakes and major volcanic eruptions. Evidence of that change was action by our Committee on Governmental Organization in creating a subcommittee dealing with the subject of emergency planning and disaster relief. The main task of that committee was to try to evaluate our preparedness system, to evaluate the beneficial links that the scientific community has, and to determine how we take scientific advice and turn it into public policy.

The work of that subcommittee, which went on for about three and one-half years, resulted in a report of findings that was both critical and, to some degree, praising of the system that we have. It recognized some problems that exist and made some recommendations. Rather than go into the specifics, I would like to explain, from a legislative perspective, what I think the main elements are in this process of taking raw scientific information and developing public policy from it.

PRIORITY, PLANNING, AND COORDINATION

Generally speaking, I think there are three main elements to any effective emergency management role. The first, and probably the key one, deals with the question of priority, and this does not only mean money. Your top leaders, the Legislature as well as the Governor and his administration, must feel that this particular subject is something that deserves attention. That sense of high priority is needed on the local level as well. It has been said in this conference that that is difficult to attain, and it is. Hopefully, with some of the things that are happening, we are beginning to change that. One of the ways that scientists can help is by developing a closer relationship with the people who make public policy. One of the problems is that the people who make public policy want advice that is either black or white. Unfortunately, in the field of geology, especially when dealing with earthquakes and volcanoes, we are not always offered advice that is black and white. But if a way is developed, on a more day-to-day basis, to bring scientific advice to the people who make public policy, I think the advice will be given higher priority. The public policy people have got to understand that this is something that they need to think about. If we can convince elected officials on the state, local, and federal levels that this is a high priority issue, we are going to get a more favorable response.

The second element that goes along with high priority is good planning. We must have planners who know how to prepare for emergency responses by allocating resources and capabilities in a way that makes sense.

The third element of a general emergency management scheme is coordination. There must be a vehicle through which all of the parties involved, whether a state agency, a local agency, a private citizen, or an elected official, can contribute and have those efforts go toward a common goal.

PREPARATION, CRISIS MANAGEMENT, AND RECOVERY

There are generally three stages of government involvement in disaster response. Prior to the disaster, responses are planned and mitigating actions are taken. There is a role that the scientific community can play here. It takes a sense of high priority to allocate the money and time to plan a response. Elected officials and people in the top administrative level have got to say that, yes, we will allocate people to plan a response. The scientific community must make the public policy community aware of potential public hazards, and convince them of the need for high priority action.

The next stage is managing the response when the disaster happens. This involves crisis management -- taking the planning and applying it in a useful way.

The third stage is long-term recovery. We need to look at how we channel federal and state funds, how they are used, and how communities recover from disasters. With thoughtful planning, we can turn the disaster into a positive instrument as well as a negative instrument in terms of long-term recovery. All three stages of disaster preparedness require high priority recognition, good planning, and coordination.

Unfortunately, in California, I don't think we have the system that we should have containing those three elements that are necessary to prepare us to deal with what I think, in terms of risk, are some very serious disasters that could happen in the state. I think there is a lack of adequate coordination. In many cases, the right hand of one agency doesn't know what the left hand of another agency is doing. There are a lot of turf problems that are involved, both in state agencies and local agencies. Alex Cunningham mentioned that local control is very strong in California and that's true. The result of that strong feeling is that people don't like to deal with large magnitude disasters that are beyond their capabilities because it is just not fulfilling to them. We have a lot of turf problems that build up from the local people, state people, and between state agencies. Unless we can start to break down those barriers, and I think that's happening, we are likely to have a response that is not coordinated. In many cases one agency doesn't understand what the other agency is doing. In fact, you may have agencies who are planning different and conflicting responses to the

same particular aspect of a disaster. That actually will negate any sort of positive reaction to the problem if the disaster occurs.

PREPAREDNESS

Another serious problem that we have in California is a lack of sufficient attention to preparedness. I think this too is turning around. Elected officials are finally beginning to pay some more attention to the area of preparedness. It is still in its beginning stages, but the Legislature is paying more attention. I know that the Governor and his administation are beginning to pay more attention to disaster preparedness. Hopefully, the result is going to be an ongoing arrangement, and when budgetary questions and allocation of staff people come up, the question of preparing and being ready for disasters, whether it's a volcano, an earthquake, or whatever, are going to receive higher priorities.

CRISIS MANAGEMENT

Another serious problem that I think we have in California, which is being addressed, but still is a problem right now, is crisis management. Some of the people from the state of Washington this morning addressed the question of who is in charge. In terms of a small or a moderate disaster, I think we have a fairly well-defined system. The mutual aid system, which Alex mentioned, can operate within the scheme allowing for local control. If you talk about anything on a catastrophic level, and people throw around the magnitude 8.3 figure for an earthquake or a Mount St. Helens for a volcanic eruption, the question of who is in charge in not clear. I can cite a couple of examples, even recent ones, which were, I think, fairly minor ones -- Diablo Canyon and the Medfly crisis. The Governor established different ways of dealing with those disasters. There is not a consistent crisis management plan in California. When the major eruption occurs or when the Great Earthquake happens, the Governor does not know who he is going to turn to to decide to be lead man in this role. There are no crisis management teams established to deal with this problem consistently. A glaring, glaring problem we have.

IMPORTANCE AND RESPONSIBILITY OF SCIENTISTS

Some of these problems are being dealt with. The Governor has established an Earthquake Task Force which is beginning to tackle some of these very important problems. It is going to be a long process and I am not going to kid you into thinking, by the end of next year, we are going to have all these problems solved. But, the problem of crisis management and the problem of high priority are being addressed. There is a role for science to play in this policy. Without scientific input, our policy is going to go off in directions that probably aren't going to benefit the public very much.

It is incumbent upon you to make that effort to relate to public policy. Unless the scientific community has improved its relationship and actually shown that its research is going to have an effect on public policy, the amount of budget support the scientific community gets from the Legislature is going to be less. You should continue to have conferences like this and be willing to play that role. Do not underestimate the importance of the role that the scientific community can and should play in public policy decisions.

DISCUSSION

Donald Peterson: Do you have any suggestions on effective ways that scientists can reach the ear of legislators and others who set these policies?

Joe Lang: The scientific institutions have to develop a more consistent strategy to get scientific information to the Legislature. One of the things that politicians and elected officials look for is advice that is black and white, that they can use to make a decision. Often times, scientific advice is not of that nature, especially in this field. But attempts to find out exactly the type of advice that can be used and how it can be used in terms of public policy, attempts of that nature, at developing that sort of communication with elected officials, could be very fruitful. It requires a certain degree of courage. It puts both the scientist and the elected official on the line.

Generally speaking, the elected official is used to that. But, the scientist, on the other hand, is not always comfortable in that position.

Question: Does the State of California have a science advisor, you know, similar to the White House advisor?

Joe Lang: At one time, Rusty Schweickart was the Governor's advisor on science policies. Since Rusty went to the Energy Commission, there really has not been an overall science advisor. Now, there are advisors in specific fields. Jim, obviously, serves as the Governor's chief advisor in terms of geologic questions. Perhaps an overall science advisor would be useful.

Harry Smith (private citizen): I would like to ask you a question I asked of Alex two years ago when he appeared over in Davis at an Earthquake Conference. In relation to activation of the emergency services in southern California, given the scenario of a major earthquake, how soon do you feel that these emergency services will be at work? In San Fernando in 1971, it was a matter of several hours before they even knew that they had deaths out in the valley.

Joe Lang: My rule of thumb would be that, for the most part, it is going to be 24 to 48 hours before any of these resources begin to arrive. Despite what Alex said about the Office of Emergency Services being a 24-hour agency, which they are, a lot of the other agencies that are involved in responding to a disaster are not 24-hour agencies. I would think that you could be looking at two- to three-day periods before the emergency services are fully activated.

Alex Cunningham: Joe is right-on on that. Obviously, you are going to have a smattering of Highway Patrolmen in the area, a few Caltrans personnel, but when we talk about significant amounts of resources from the state level, they will have to be moved in from outside the area. Joe Lang is using the exact figure that we are using for planning purposes -- 24 to 48 hours. With the possible exception of some doctors, we might be able to get them in a littler sooner -- 12 hours. If you don't get them in within 12 hours, you have problems.

Harry Smith: I noted that in the two years that have elapsed since I asked that question before, the answer you gave, as of that date, seems to me still to be the same. Is there no hope for improvement?

Jim Davis: I think the critical thing is the delay in which state-based resources can be brought into a natural disaster area. I'm among a number of people who are trying to work on planning for the disaster from a physical point of view. Now, if the disaster can be predicted, then the response time can be reduced, and that, plus a few mitigating measures, is the principle advantage of being able, from a public policy point of view, to have foreknowledge of the event in terms of specific time, place, and size. The other thing that has to be done is to improve our understanding of what the outcome of the event would be so that that knowledge can be used in response to the event when it takes place. For instance, in a large earthquake on the southern San Andreas fault, it would be critical to know in advance what highways will be open and what airports can be used -- just to give you a general example. If we have improved our confidence in those outcomes, then it makes sense to plan for either the absence or the presence of those facilities in an operating form during the emergency. So I think both are critical: being able to anticipate the nature of the event and its effect on the lifelines that we use to respond to it, and also having foreknowledge of the event itself for preliminary mitigation. Now, if you don't have either one of those, then you are not in very good shape to plan; and in a catastrophic event, as Joe was saying, we would be overwhelmed in terms of being able to provide response. In that case, local communities can expect to fend for themselves for a period of up to 24 hours, or even beyond under some circumstances.

PANEL DISCUSSION III

APPLYING THE STATE OF SCIENTIFIC KNOWLEDGE AND RECENT VOLCANIC HAZARDS EXPERIENCE TO CALIFORNIA'S EMERGENCY RESPONSE STRATEGIES

Moderator: Gilbert F. White

Panel:
Roy A. Bailey
Alex R. Cunningham
Robert W. Decker
Jack D. Kartez
Joe Lang
Robert A. Matthews
C. Dan Miller
Donal R. Mullineaux
Les Nelson
Donald W. Peterson
Clement F. Shearer
John H. Sorensen
Robert C. Stevens

Gilbert White: We bring to a close what has been a long and instructive set of presentations and discussions. We've been favored in having a series of informative, thoughtful, and provocative statements. We haven't had as much opportunity for discussion as I expect most of us would have liked, but we have managed to canvass, with the benefit of some very well-informed scientists and administrators, the range of issues. We shall next ask for a series of brief statements from each of the persons on the the panel, and then, allow statements from the floor by people who disagree or want to register dissenting statements about the wisdom that has been dispensed before. At the very end, we will have a minute or two of comment from Jan Denton, Jim Davis and Alex Cunningham to close the session.

I think there are some points that this workshop has covered rather adequately that don't need extensive comment at this stage. First, there has been quite discerning delimitation of hazardous volcanic areas in the State of California. Second, there has been rather thorough examination of the limitations and opportunities for monitoring volcanic events and the precursors of them. There has been candid recognition of the opportunities and the limitations of our ability to make predictions at various time horizons with the present state of scientific knowledge and there is a need for deepening scientific investigations to, in time, increase that capability. If we start from that, we can then ask: what are some of the issues that have not been as clearly resolved? In our closing minutes, ask yourselves whether there are points that you would like to make or emphazise for the benefit of the whole group with respect to those issues. I'm asking people in the panel each to speak not for more than two minutes on an important issue or an important conclusion they feel either hasn't been considered or deserved special emphasis. I'm going to begin with Clem Shearer.

Clem Shearer: I think a particular point of concentration, from my perspective, which is that of a scientist trying to work more intimately with public officials, is that in

order to improve our relationship, we are going to have to understand the limitations of the civil authorities. That is, we have to learn what it is they can do, and what it is they can't do. We have to understand they will lack certain capabilities, they will lack certain resources, they always will lack it and probably justly so. We should not expect to train them as geologists or as any other scientists. It will perhaps be more incumbent upon us to figure out how we can work with them more closely to make up these deficiencies. I think that is going to take a bit more attention than we have given it in the past. We have a lot of instruction from behavioral and social scientists, and we have a lot of experience from Mount St. Helens and other geologic phenomena of which our offices tried to warn public officials. I think careful analysis of what has worked, what hasn't, and why it hasn't will provide adequate guides, given proper manpower resources, for the survey or for any other scientific organization to breach this gap and make up some of the deficiencies some scientists like to say exist in the civil authority.

Roy Bailey: I'd like to reiterate one of your comments of last night, Dr. White, that, in a sense, we have lost some of the momentum and public interest that Mount St. Helens generated this past year, but, in spite of that, now is the time to communicate with the local community. We haven't lost the local interest, and as coordinator for the Volcanic Hazards Program with the survey, I've been most concerned because we have been cut back in funding, and are not going to be able to do the things that we wanted to do scientifically in monitoring the Cascades. But at the same time, we haven't lost everything. Our ability to communicate our experiences and what needs to be done for the public, particularly, the local public, has not been lost. Now, is the time to do it!

Robert Matthews: I'd like to talk, very briefly, about communications. I have had some very limited experience in communications with nontechnical people, that is, scientic information to nontechnical people. So as a non-expert, I'll talk about that. The discussion of communication was mentioned last night by Dr. White and again today by Joe Lang in a sense that I want to talk about. Communication is certainly most important when we talk about how we are going to deal with the problems of hazards and the disasters that take place, but one of the things important, I guess, is that irrespective of the quality of the work the research scientists develop, if the material is not communicated in a very precise manner -- and I want to use that term "precise" in emphasis, a precise manner to these people, then it doesn't matter what the research is. I think what we need to do is to be very precise when we use terms that are important to these people who are both decision makers and policy makers because they are the ones that are going to put into action the benefits of the research. One word that was used here quite a bit, and I want to just use this as an example, is the word, "prediction." Prediction means different things to different people. A very precise manner would be to define prediction as exact time, place, and magnitude. Of course, we have heard we cannot do that with the present state of the art in volcanic prediction. Other modifying terms that were used were: "probabilistic" and "deterministic." What do those terms mean? The kinds of things that I think that we need to concern ourselves with is giving precise definitions of terms like "deterministic" and "probabilistic." So, when these people get this information, it really means something to them that they can transpose that into real action.

Joe Lang: The first thing I would like to say just capping what my comments were, we do have some problems in the preparedness field, and I'm not going to try to tell everybody that everything is "rosy" and that we can do everything, but there are some initiatives that are being taken to deal with them. For example, the Earthquake Task Force, and some of the other things that the administration is doing. Even more importantly, I think, there is a role that you could play, and I think that what Clem Shearer said was perfect. Elected officials, the Legislature, public policy people -- we do have deficiencies, and I'm willing to say

them right now. Basically, our deficiencies are: number one, I have very little expertise; number two, I have very little knowledge; number three, we, as representatives, have been elected and given the power to do something about these problems. So, unfortunately, we have only one of the three components that are required to make decisions. Those are my deficiencies, and those are what the Legislature's are. What we need from you earth scientists is information on which to base those decisions, information which we can understand, information that is useful, that is applicable to the everyday situations and types of information that we get.

Alex Cunningham: First, I do agree that we need improvement in the system, and to do this, we all do need to work together. Secondly, I want to point specifically at the Legislature. For years, it kind of fell on "deaf ears," but in 1979 the Assembly Governmental Organization Committee, with the Subcommittee On Disaster Preparedness, did start to look into the system, and I'll be the first to tell you, I resisted it. I was like the turtle in the shell; I pulled my head in and said, "By God, let 'em knock all they want." Then, I stood back and said, "Hey, you know, these guys are trying to help us, and we do need and want help." Since then we have been working together to try to improve the system. I think that all started with Assemblyman Vicencia's Subcommittee On Disaster Preparedness, and I see that also continuing, not only for that committee, but with Senator Campbell's Joint Committee on Fire, Law, Emergency, and Disaster Services.

Thirdly, in the discussion at the end of the question period with Joe Lang, a gentleman from the floor asked, "Have we made progress in the last two years?" I would say, "Yes, we have, very definitely." We know that it is still going to be 24 to 48 hours before all the resources can be brought to bear. For example, the medical resources. The Department of Health Services has devised a very fine medical response plan which can deliver 200 doctors in an hour, and 500 doctors in two hours to an airport in San Diego or San Francisco so they can be flown in to the Los Angeles area. That doesn't mean they are going to be on the scene in one to two hours, but we are looking at maybe four to six hours when it is still possible to save lives.

The last point I'd like to make is that I know that we are better prepared than Washington State to handle the situation. No, I'm not patting myself on the back. I know we are better prepared because of what we learned from their situation at Mount St. Helens -- I'm talking just about volcanoes now. Had it not occurred, we probably would not have taken a good, close look at the volcanic hazard situation in California. Because it happened, we are now in a better mode to respond because of the experiences we were able to gain from that situation. Finally, what I think we need to concentrate on is a better system of quickly identifying the emergency response resources or resources status system so that we can respond effectively to local government when the situation occurs. We look forward to working with the Legislature, to working with local government, to continue to streamline and improve the system.

Robert Stevens: Looking from the regional standpoint, I think I'd have to say "Amen" to what Alex said about the State of California and the State of Washington. I think I'm a relatively impartial observer, having had significant and long-time experience in both of these areas. I used to live in Washington State, and I was a Regional Director in this region for nine years prior to my retirement. So, I've had a fairly significant involvement with both of these states, and I can absolutely assure those local government officials there that California is a long, long way ahead of where Washington was eighteen months ago. But there have been some changes up there too, I can certainly emphasize that. The other thing I would touch on is the political aspect of disaster relief and disasters. There are two important sides to having a President of the United States visit a disaster area from my perspective. For example, the first thing, and this is very important for a bureaucrat, the first thing he does is give you tremendous visibility. There is absolutely nothing that I know of which will give you more identity quicker than to sit down beside the President of United States and turn the media loose to take your pictures.

Very effective -- and that's very positive when you are dealing with the other bureaucrats, because when you talk to them, they listen. The very, very negative aspect of that is that everybody else thinks that somehow you are now going to "walk on water." (Whereas, in fact, you can't even swim.) And so, everybody expects you to do a great number of things that you really can't do. The truth of the matter is, in big disasters politics always plays a very critical role. You get involved with Senators and Congressmen and Governors, and, you know, when I went up there, I had a full head of nice brown, wavy hair. (Laughter.) You really get that side of it. Politics is very real. The scientific community, and I would pat the USGS on the back, I don't think that they ever succumbed to political pressure up there. I don't think they ever took a position that they could not back up scientifically because they were under pressure politically to do something. I witnessed Mr. Carter asking Don Mullineax some pretty penetrating questions, and, of course, Jimmy Carter, as you know, is a scientist. This was true of USGS generally. They did maintain their integrity, and I was very pleased about that, but you have to deal with political issues. You have to deal with politicians, and that's a very real aspect you ought to maintain an awareness of.

Sheriff Nelson: Well, I have to agree with Clem that it's time that he did learn about some of our deficiencies because we sure learned the other side of it in reverse. (Laughter.) Communication has always fascinated me -- to talk with people and try to understand them. I triggered a reaction here today when we talked about "who is in charge," and ultimately, some stood at the back of the room and became rather defensive. I'll only go to this point by saying that we moved somewhere between 12 and 15 hundred people in a matter of a couple of hours out of the danger zones. We rescued 192 people, and no one was killed after the initial blast. Somebody must of had their act together! Enough of that. About communications, the way we hear things that are said and the way that they are translated real quickly -- reminds me of the matched horse race between the Russian and the American horses that they held in England (a two-horse race). Naturally, we beat 'em bad, I'll tell you that up front. But the communique that came out in Russia said, "Our horse ran second, and the American horse ran next-to-last." You can do things with words that people tell you. I spoke earlier about the need for a common language, and you heard a lot of that today -- understanding what people can do for you, what are they really talking about -- a lot of that needs to be done. I would hope that people from the scientific community would actually physically go and make some kind of contact with the representatives in your area. How many of you know your sheriff? Some people would rather not, and I understand that. (Laughter.) But communication is the big thing with me. Once you get to where you can talk with people, then the good things are going to happen.

Jack Kartez: I can share with you some of my concerns and hopes as a planner and a community resource developer, which is a person that helps people solve problems and helps build the capacity to solve problems. I keep hearing the theme of "common," and I am very concerned about that. I would like to pick up on something that Alex said earlier when asked, "Does the State of California have a volcanic eruption response plan?" He said, "We have a generic plan." I think that's exactly what's needed. I am very concerned about the tendency to say this is a plan, or strategy to respond to, or plan for, or mitigate this type of hazard. That may be true in many, many areas in terms of prediction and understanding the hazard and how it works physically, how it may work physically and mentally on human beings, too. But, in terms of organizing the community, in a larger sense, and all levels of government, too, to respond -- they are all the same at one level. To give you an example, Jerry Brown told about some things that the Forest Service learned, playing the leading role that they did over on the west side of Washington. He said, "Look, we learned that we had to move our communication system for operations out of the same building that we were using for media and other public communications so that we could get our work done." That is exactly what happened in Yakima. They eventually moved their operation communication

center out to a building away from City Hall, where there was just too much going on to get the work done. So that's a specific example.

The last comment I want to make -- which I think we saw some evidence of at Mount St. Helens, at least with the work we did with cities and counties -- is that our ability to organize and work with citizens in an emergency, and the ability to work intergovernmentally between state, federal, and local levels effectively, is, I think, partly dependent on an ongoing process of capacity building and problem solving on an ongoing type of community planning basis. I've heard so many comments about how hard it is to sell emergency response or preparedness planning over the long term when there isn't an imminent hazard -- some sexy hazard that is going to bring it in the forefront in people's minds. That's true, the same thing is true with planning for housing, and jobs, and adequate public facilties and services, and other human services, and so on. In law enforcement, it is true too. It is hard to keep the community interested. I think the two go together.

This is a time when we are pulling back from an investment in general community capacity-building and problem-solving programs, or planning, whatever you want to call it, and I think this trend has implications for those with specific interests or responsibilities in emergency preparedness planning.

John Sorensen: I'm going to disagree somewhat with Jack. I hope that perhaps within the next year that Alex and Jim might be sponsoring another workshop in which the prime concern would be not to explore some of the problems associated with managing volcanoes, but rather to review and critique California's policy for dealing with volcano hazards, a policy that would be based upon the studies that the USGS is starting to come out with, and to review and critique the kinds of emergency response actions that would be necessary to actively mobilize at a state and local level for coping with some of the specific types of hazards that are beginning to be identified. And, so, I think what's needed is to go beyond a workshop like this where we identify problems and needs and put those needs and problems into actual practice.

Gilbert White: Don Mullineaux, you've been through this now in one area. What about another?

Don Mullineaux: First, "amen" to Les Nelson's statement that local officials had their act together. That's one of the main things that remains in my mind -- being immensely impressed by the local people who had to make the difficult decisions. As far as what's next, prediction is the big thing in my mind. We need to not only define those terms better, as Bob Matthews points out, but we need almost desperately to learn to do better in formulating both the specific predictions and the probabilistic predictions. We need to better explain to the people who have to use them exactly what they mean. And, last, something that Dan Miller pointed out to me after I was talking earlier, is that there is a cost to probabilistic predictions, and that is, because they are uncertain. It's like the weather, even though there is 90% chance of clear sunny weather, you may get hit in a downpour. If we are to be careful enough to warn people so that they do not get caught unexpectedly in some kind of catastrophic eruption, we've got to be prepared, and those public officials who use our information have got to be prepared to catch the flack when we end up in the position of having cried "wolf." If we use probabilistic predictions, we are going to be wrong some percent of that time.

Don Peterson: We are faced with that kind of situation right now at Mount St. Helens. The hazard has subsided this past year. Chris Newhall, the present Hazards Coordinator at Mount St. Helens, has attempted to express the hazards risk in a quantitative perspective and has a manuscript in the mill right now. The information that he based his figures on is based on what was happening during episodic explosive eruptions. But, for over a year now, we have had nothing except quiet dome-building eruptions. We have had about seven of these. I think that this is sufficient experience to indicate that the volcano is in a quieter mode. Also, the

survey has developed some confidence in predicting these individual events. This combination of prevailing quiet and our ability to predict with some confidence, I think, enables the zone restrictions to be relaxed to some extent, and there are active discussions going on now among the Forest Service, the state officials, and the county officials about working out a scheme by which the restricted zones can be shrunk. A lot of this is based on the Geological Survey's confidence to be right. The advantages to be gained by this are improved understanding by the public. They can then get in and see the devastation that was wrought and learn something about the volcanoes. Its going to greatly ease the ability of the industry to work in the area and many other benefits will accrue to society. But if we happen to be wrong a certain percentage of time, we're going to have to take the heat. So, this is indeed a problem.

Another topic: I think it is very, very important that scientists have the chance to listen to the problems of the law enforcement officials and the public policy makers. There are all too few opportunities for those of us who get wrapped up in our scientific problems to really listen to what these people have to say. This kind of conference is a splendid opportunity for my colleagues and myself to hear and listen to these problems, and I just hope that those of us who are fortunate enough to be here can translate some of the things that we have heard to our other colleagues who aren't here. I think all of us as scientists tend to get very much wrapped up in science for science's sake. We get excited about the problems we are trying to solve, and we don't carry over what their benefits are to society as a whole. I think, in part, this follows up what Roy has to say in that we are not effective in somehow conveying this need to our funding agencies, and we end up short. It is all a problem of effective communications and hearing everybody who is part of the equation.

Gilbert White: We've made a tradeoff in the interest of making sure that each panel member had his say. We haven't structured the discussion, but as you can see, it has tended to focus on a couple of points or themes that have been repeated and emphasized. Now, we would like to invite those of you that would like to, and to the extent of the time available, to contribute your views.

Bob Decker: I'd like to carry on where Bob Matthews left off. I'd like to make the plea that, in general, we use the word "forecasting" rather than "predictions" for the simple reason that the use of the word "forecasting" by the weather people already gives it a probabilistic connotation, where many people, when you use the word "prediction," infer that you mean something very precise, and when it doesn't happen, the "cry of wolf" is much louder when you've said "predictions" than when you've said "forecast." That has been my sad experience.

Gilbert White: Like "predictions" of national budget deficits? Dan Miller, you haven't put up your hand, but I think we really ought to hear from you.

Dan Miller: I think there are four main areas in California where volcanic eruptions are really possible in the near future. Those are the Shasta area, the Lassen area, Mono, and Medicine Lake. There are others as well on my volcanic hazards map. In each of these areas, I would hope that we could begin to have more cooperative workshops and working relationships between the U.S. Geological Survey, the U.S. Forest Service, the Park Service, and state and local agencies. There are several reasons: one of them, I think, is that the cooperation between the U.S. Geological Survey and the Forest Service at Mount St. Helens was an extremely productive relationship, and it resulted in the situation being handled reasonably well. I think that we could begin to think about this sort of cooperation in the future -- including looking for possible future sites for setting up an emergency communication center in some areas in California, should it become necessary. Where would we get the necessary communications equipment on short notice? At

Mount St. Helens, for example, we needed 50 radios and some repeaters on very short notice. Other types of logistic support could be needed in as little as a few days. For example, helicopters and other types of aircraft. So, I think for some of these areas in California, we could at least begin to think in terms of specific needs that could arise on a short-term notice.

Al Lockhart, Office of Emergency Services: I would like to address the subject just raised by Dan Miller and refer it to Clem Shearer. As you know, we had an excellent workshop at Mt. Shasta based upon some the work that Dan Miller did, and we would like to continue the operation, as he suggests, at places like Mono Lake, which we understand that Dan Miller is going to investigate. My question to Clem is, "What is the status of your budget for it? Are we going to be able to take advantage of that?

Clem Shearer: I should have a better idea of what the budget is when I get back to my office. The office will still be there. I don't know whether it is going to be occupied or vacant after Monday (laughter). The plan was, as contrived under a low budget that we had prior to fiscal 1982, to hold similar workshops in every volcanic hazard area after the geologic and hydrologic work has been completed, ideally, after a report such as Dan Miller's Shasta report, or the Crandall/Mullineaux Mount St. Helens report, has been published. If a hazard seems more imminent, then we should perhaps move before our reports are actually out of the press and just present what we have. We've included in that budget at least one more for the next year. The one that was listed is not in the State of California, but we would like to return to some of the areas that Dan has mentioned to cover those.

Gilbert White: You have to balance the problem of adequate financing against the sense of urgency and grasping the opportunity of public receptivity and interest. Others that want to speak here or raise questions? Yes, Roger.

Roger Martin: I would like to throw a question to the panel, specifically in California, what types of volcanic research are most needed at this point.

Roy Bailey: I think, perhaps, more than monitoring, we need volcanic hazards mapping of the type that Dan is planning to do in Mono, and that has been done at St. Helens. In areas where something is obviously going on, as I described at Mono and Long Valley, we have to continue doing some kind of monitoring. In the long run, it's the volcanic hazards mapping which is going to allow us to make the kind of forecasts that are going to pull us through.

Don Peterson: I fully agree with what Roy said. There are just a whole bunch of volcanoes, both in California and in other parts of the U.S., that desperately need this kind of mapping. In addition, I think this sort of hazard assessment study takes on its fullest meaning when complemented by basic geologic research -- and here I refer to the type of study Bob Christiansen described yesterday for Mt. Shasta, or the kind that Charlie Bacon is doing currently at Crater Lake, or the kind that Roy Bailey has done at Long Valley. My point is that we get the fullest picture of volcanic systems when we combine the hazards approach, with its focus on the volcanic history and the frequency of eruptions, as in the research of Dan Miller and Don Mullineaux, with the classic approach, which looks at the all-around geologic and petrologic history. The two approaches, together, provide the best means of anticipating what a volcano might do.

Ben Lofgren: Yesterday, Professor McBirney described Mount St. Helens as kind of a unique feature. Are we anticipating that the volcanic hazards such as occur in California are going to be another Mount St. Helens? or could it be something totally unrelated? As, for example, mudflows unrelated to an explosion? Almost everything that has been said here is implying that we should be prepared to address another Mount St. Helens in California, but I

can visualize a hundred and one other types of volcanic hazards which might occur before that happens.

Don Mullineaux: The kinds of hazards that were present and are present at Mount St. Helens are certainly characteristic of the Cascade Range volcanoes in northern California. Mudflows are one of those types. All of these words that we throw around such as the "volcanic ash threat" or "tephra," the "pyroclastic flows," the "floods," the "lava flows" -- all of those things have occurred at Mount Shasta, the Lassen Peak region, and the area around Medicine Lakes. The Mono Lakes, Inyo Craters, Mammoth Mountain area is somewhat different in that the volcanoes there are smaller and characterized by dome extrusions and very explosive eruptions of somewhat limited extent compared to those of Mount St. Helens, but they would be extremely destructive in that area. I'm not sure what you are thinking of in the many, many different kinds of hazards that would be characteristic of California that have not been exhibited at Mount St. Helens, perhaps you'd expand on that.

Ben Lofgren: I'm thinking beyond that. Are we planning in terms of the next hazard occurring within a very brief period of time, with virtually no warning, and going into the situation pretty much unprepared? Or could it be a volcanic event that is building up, that we know is going to be happening, and we have a lot of advance warning? In that case, when does the signal go out? when do we address the problem? When does it become an emergency?

Sheriff Nelson: My comment would be to prepare for the worst and hope for the best. Then it's easy to go downhill from there. It wouldn't hurt if you geologists got some contact in your community. Get some signs on the side of your car and park on main street in these areas where you are doing your work. Nobody ever knows you are there. Contact some people. Say: "How do we get the public interested?" Let them know there is a geologist in the area working on the mountain, and you will find out where the interest comes from. That opens the door for some of the rest of us who then have to start talking about these things. You are probably going to create a little excitement, but that's not too bad for your life either.

WORKSHOP SUMMATION AND CONCLUDING REMARKS

BY: Gilbert White, Director
Natural Hazards and Applications Information Center.
University of Colorado.

James Davis, State Geologist
California Division of Mines and Geology,
Department of Conservation.

Alex R. Cunningham, Director
California Office of Emergency Services.

Jan Denton, Director
California Department of Conservation.

Gilbert White: Friends, there are others that want to speak, but we have to bring this to a close. I want to speak on behalf of all the rest of us in expressing appreciation to the California Department of Conservation and Jim Davis and his colleagues, and to Alex Cunningham and his colleagues in the Office of Emergency Services for having brought us together and provided such a congenial and candid exchange of information, experience and questions.

Alex Cunningham: Thank you, Gilbert. A most masterful job of directing this discussion. I have had the privilege of working with both Jan Denton, Director of the Department of Conservation, and Jim Davis, and it's been a real pleasure. Gilbert, we are indeed pleased to be co-sponsors of this event along with the Department of Conservation and Jim, and I would like to recognize for a moment the hard work that has been put in by not only the Department of Conservation and by the Office of Emergency Services staff people, but also the U.C. Davis Extension group headed by Barbara Zaro that has hosted this event, and made sure that when you push the right buttons, the right slide comes up and things like that. A great job there. For the entire audience, I think you are truly a talented, interested, and dedicated group, and also very tireless, as evidenced last night. I think, in closing, that sessions such as these do a great deal to raise the awareness level, and ultimately will improve and have a very big impact on the overall emergency preparedness system.

Jim Davis: It has come to my mind that perhaps we have not mentioned public education in our discussions here. We need a base level of communication about some of these phenomena, particularly in the areas where there are potential problems that we haven't explored. I think that is something that we need to look into because we can't expect intuitive understanding to really be very much of a guide. This has been brought home to me not only by what has been said in this room, but by the interviews that I've had as a result of this conference where people who are in the media area are incredulous that there is volcanic activity or the prospect of volcanic activity in California. So, if that's true in the media, God help us for the rest of the people in the state. Communications and

research have emerged, not surprisingly, as the principal emphases of the workshop, and I would submit that our strategy for communication -- I love the sheriff's image of a rat in a roundhouse -- our strategy for communication should be something that evolves along with the results of our research. It should be a strategy which recognizes that the perspectives we have here today are not going to be the same scientifically as those we will have three or four years from now. Hopefully, we will be turning some corners in deterministic strategies of prediction. If that is true, then, we are going to be communicating in a different way. We will have a somewhat different message, and that means that we on the science side have to be involved in a dialogue which is evolving along with our scientific understanding, and that there is no communication that can be static any more than our research results are static. Those are the things that I feel I have learned, and I am very gratified with the time and effort that the participants have made available and also with the interest and participation that's been shown by those in attendance. I want to thank everyone for that.

Incidentally, I want to correct an oversight I've committed every time I've been in front of the microphone. Gordon Oakshott, an eminent scientist and emeritus State Geologist, who has published widely on California geology and volcanoes, has been attending this meeting. I would like to acknowledge his presence. Thank you.

Jan Denton: As a non-scientist, I am impressed with the caliber of the participants in this two-day workshop. Jim and his staff did a superb job in convincing all of us of the value of such a conference. And so, I again would like to personally express my appreciation for your participation.

Over the last two days I became particularly aware of the necessity for public education on this issue, and I was very pleased to see the amount of interest shown by the press. In a natural catastrophe of the magnitude of Mount St. Helens, the extreme pressures of the media strain the capacities of agency personnel and officials. One important area to focus on in future emergency planning is the development of systematic communications with the press because they represent the critical unit between us and the public. We forget how important it is to keep the public informed, especially today, when the mood is so definitely anti-government.

So, I encourage you, especially those of you who are scientists, to have a little more courage in speaking out about your convictions. I know you are concerned about the scientific validity of the information you have to share, but an occasional update of your activities is very beneficial. Conferences such as this are enormously educational, especially for the non-scientist.

I personally feel reassured knowing that we have a fairly long time period in which to predict an earthquake or a volcanic eruption, and that this allows us to give out information far enough in advance for the public to be prepared. Public officials need to understand the limitations under which scientists operate, take into account the odds on a certain event happening at a given time, and have the courage to act responsively. This kind of partnership is what makes government work the best. We are all here trying to work in the public interest.

I am very pleased with the two-day workshop and the opportunity we have all had to communicate with each other. I hope that we can continue this sort of communication and constructive planning in the future. Thank you.

LIST OF PARTICIPANTS AND REGISTERED ATTENDEES

Alfors, John
Allen, Cynthia
Alt, John
Arvidson, Paul
Avent, Jon

Bacon, Forrest
Bahl, Bill
Bailey, Roy
Barrows, R.
Bell, David
Bezore, Steve
Bice, David
Birdsall, Lucy
Borum, Jeff
Boyd, Francis
Brown, Jerry
Brown, William
Buffaloe, L.
Bullard, Fred
Bullen, Thomas
Burton, Robert
Bushnell, Marjorie

Cameron, Chris
Campbell, H.
Cardinal, Ann
Caress, Mary
Carr, Wilfred
Cashman, Patricia
Cashman, Susan
Chesterman, Charles
Christiansen, Robert
Clynne, Michael
Cole, Judy
Cole, Ken

Coleman, Eugene
Collins, Kelly
Corso, A.
Crosby, Tom
Cunningham, A.

Davis, Devere
Davis, James
Dawson, Paul
Dawson, Phillip
Decker, Robert
Decker, Barbara
Deino, Alan
Depolo, Craig
Denton, Jan
Downey, Robert
Dresen, Michael
Dutra, Maryjo

Edmondson, Betty
Ehlig, Kathleen
Ethier, Henri

Fernbaugh, Mark
Fielden, John
Fields, L.
Fisher, Richard
Friedman, Jules

Gallagher, John
Gamble,
Garrett, L.
Gill, James
Ginsberg, I. William
Goldschmidt,
Grose, Thomas

Habiger, Frank
Hait, M.
Hansen, Frederick
Harris, Stephen
Hartep, Russell
Haskins, Don
Hawkins, Bruce
Hays, Thomas
Hembree, David
Hempree, Susan
Herbst, Charlene
Higgins, Chris
Hirschfeld, Sue
Hohback, Paul

Jackson, Larry
James, Stephen
Jephcott, Donald

Jestes, Edward
Johnpeer, Gary
Johnson, Frederic
Johnson, James
Johnson, Marti

Kartez, Jack
Keithley, George
Kienle, Rick
Kienle, Juergen
Kilbourne, Richard
King, Charlo e
Knight, Kenton
Kreske, Diori
Kwolek, Albin

Lang, Joe
Layton, Donald
Lefevre, Harold
Leivas, Eddie
Leydecker, Allen
Licari, Joan
Linkletter, George
Lockhart, A.
Lofgsen, Ben

Mackey, Sandra
Mackowski, Mark
Malone, Steve
Marliave, Burton
Martin, Roger
Matthews, Robert
McBirney, Alexander
McCauley, Marvin
McCrone, Alistair
McDaniel, George
McJunkin, Richard
McKee, Bates
Medigovich, W.
Melson, William
Meehan, John
Melickian, Gary
Merrill, John
Miller, C. Dan
Moran, Douglas
Morganthaler, John

Morrice, Martin
Mote, Peter
Muffler, Patrick
Mullineaux, Donal

Nelson, Les
Neslen, Robert
Nicholson, Pierina
Nolf, Bruce
Norton, Joe

Oakeshott, Gordon
Odgers, Irving
Oliver, Elizabeth
Orourke, Edith
Orr, William
Ostby, C.

Palmer, Jeff
Palmiter, Daniel
Parker, Jane
Parker, Malcolm
Peterson, David
Peterson, Donald
Pierson, Ann
Pierson, Fred
Pringle, J.

Rasmussen, N.
Reynolds,
Reynolds, Stephen
Rice, Raymon
Riddle, Linda
Roquemore, Gleen
Rose, Merwin

Saucedo, George
Shaw, Herbert
Shearer, Clement
Shulters, Michael
Sieh, Kerry
Smelser, Mark
Smith, Genny
Smith, Harry
Smith,
Smith, Robert

Smith, Ted
Smith, Ward
Sorensen, John
Stefanides, Neil
Steller, Dorothy
Stevens, Robert
Stork, Allen
Stroh, James
Stromberg, Peter
Summerfield, Glen
Suneson, Neil
Sutliff, Rod
Sutton, Imre

Talley, Michael
Tanaka, Janet
Tapper, Charles
Thomas, Carol
Thompson, Robert
Toppozada, Tousson

Vance, Richard
Vanhouten, Gary
Vanvelsor, Joan
Verosub, Kenneth

Watkins, J.
Watson, Phillip
Watts, Michael
Wehmeyer, Larry
West, Don
Whear, Allen
Whelan, Peter
White, Gilbert
Wiggett, Gail
Wilcox, Ray
Wilhelms,
Willard, Syd
Wilson, Richard
Wojcicki, Andrei
Woods, Mary

GLOSSARY OF VOLCANOLOGIC TERMS

airfall deposit	Pyroclastic fragments that have fallen from an explosive crater eruption or eruption cloud. Its distribution is largely downwind from the eruptive vent.
amphibole	A group name for common hydrated rock-forming minerals high in iron and magnesium.
andesite	A volcanic rock type intermediate in composition between rhyolite and basalt.
aphyric	Texture of a fine grained igneous rock that lacks larger crystals (phenocrysts).
ash, volcanic	Pyroclastic material, of approximately sand and dust size, formed by explosive volcanic eruptions. Tephra.
ashfall	A shower of airborne volcanic ash falling from an eruption cloud. A deposit of volcanic ash resulting from such a fall and lying on the ground surface.
ashflow	A rapidly moving, extremely hot mixture of volcanic gases and ash, traveling down the flanks of a volcano or along the surface of the ground, produced by the explosive disintegration of viscous lava.
attenuation	A reduction in the amplitude or energy of a signal, such as weakening of seismic waves with distance or by passage through less rigid rock material.
basalt	A dark, mafic lava rock rich in iron and magnesium and comparatively poor in silica.
breccia	A coarse texture rock composed of large and small angular components.
calc-alkaline	Igneous rocks of specific CaO and K_2O+Na_2O and SiO_2 relations characteristic of tectonic environments such as the Cascade volcanic province.
caldera	A large volcanic basin-shaped depression generally formed by collapse of the roof of a depleted magma chamber.
Carbon 14 age dating	Determination of the age of a material by measuring the proportion of the isotope C-14 (see "radiocactive age dating") in the carbon the material contains.
cinder cone	A steep conical volcano formed by the accumulation of cinders and other loose material expelled from a volcanic vent by explosive eruption of lava.

cinder, volcanic	A cinder-like pyroclastic fragment of vesicular (bubble-filled) lava.
conduit	The subterranean path or crack through which magma moves.
closed-vent phase	The early, explosive phase of a volcanic cycle prior to the magma's unrestricted venting at the surface. Characterized by fumarolic, seismic, and phreatic (steam blast) activity.
crystalline rock	A hard rock composed of interlocking crystals; often of igneous origin. "Basement" rock of the continents.
crystal tuff	A tuff that consists predominantly or conspicuously of crystals and fragments of crystals in a finer grained matrix of glass particles.
dacite	A silicic volcanic rock intermediate in composition between rhyolite and andesite or basalt. Dacite lavas are viscous and associated with explosive volcanism.
debris flow	A moving mass of rock fragments, soil, and mud, more than half of the particles being larger than sand size. Term is used for both volcanic and non-volcanic mass wasting phenomena.
deterministic process	A process in which there is an exact mathematical relationship between the independent and dependent variables in the system.
deterministic prediction	A prediction based upon geophysical or other precursors, expressed in relatively precise time location and magnitude parameters.
differentiation	Processes, such as gravity settling, partial crystallization or ionic diffusion, by which magmas or zones within magma of different compositions are produced.
dome, volcanic	A steep-sided mass of viscous lava forming a more or less dome-shaped or bulbous mass over and around a volcanic vent.
dry tiltmeter	An installation of three or more survey monuments among which vertical movements are measured with a leveling instrument to determine ground tilt or deformation.
dust, volcanic	Fine, dust-size particles of volcanic ash.
effusion eruption	An eruption of lava to form a flow or dome (as opposed to explosive eruption).
epicenter	The point on the earth's surface directly above the origin (focus) of an earthquake.
explosive index	The percentage of pyroclastics among the total products of a volcanic eruption. See "volcanic explosivity index."

feldspar	A light-colored, rock-forming mineral composed largely of silicon, oxygen, and aluminum.
flank eruption	Eruption from the side of a volcano (in contrast to a summit eruption).
focus	True center of an earthquake, within which the strain energy is first converted to elastic wave energy.
fumarole	Hole or vent that emits fumes or vapors.
geophysics	The physical and mechanical aspects of geology (in contrast to geochemistry or classical geology).
geothermal energy	Energy derived from the internal heat of the Earth.
glass (volcanic)	Quickly chilled amorphous lava material. Non-crystalline matrix of a lava or tuff. Also, the still molton matrix of a partially crystalized lava or magma.
graben	A down-dropped block of earth bounded by faults on either side.
harmonic tremor	Continuous oscillating ground motion with frequencies of 0.5 to 10 Hz, associated with volcanic eruptions and in particular, subsurface magma movement. Volcanic tremor.
hydration-rind dating	A method of calculating the age in years for a Holocene volcanic or obsidian artifact glass by determining the thickness of the hydration rim which has been produced by water slowly diffusing into a freshly chipped surface and producing a hydrated layer or rind.
hydrothermal reservoir	An underground zone of porous rock containing hot water.
hypocenter	The intial rupture point of an earthquake, where strain energy is first converted to elastic wave energy; the location is defined by latitude and focal depth.
ignimbrite	A tuffaceous or lava-like volcanic rock or rock unit formed by a massive pyroclastic flow eruption. An example is the Bishop tuff erupted from the Long Valley caldera area 1,700,000 years ago. Such colossal ignimbrite eruptions are prehistoric, never having been witnessed by modern man.
intrusion	An igneous rock body formed when molten igneous rock forces its way into surrounding host rocks and then cools; also the process of forming such an igneous rock body.
lahar	A volcanic debris flow or mudflow of pyroclastic material on or from the flank of a volcano.
lapilli	Rock fragments thrown from a volcanic vent, defined in the size range 4 mm to 32 mm in diameter. Coarse tephra material.

lava	Magma or molten rock that has reached the surface; or the resulting solid rock after cooling.
lava dome	A steep-sided, rounded extrusion of lava, squeezed out in a viscous form from a volcanic vent.
lithic tuff	Tuff in which rock fragments (of ash and lapilli size) are the dominant constituent.
mafic	Magnesium and iron-rich rocks. Mafic lavas are dense, dark gray to black rocks, the most common of which is basalt. They have low silica content, in contrast to rhyolite and other silicic volcanic rocks.
magma	Molten rock material in the earth, with dissolved gases, that forms igneous rocks on cooling. Magma that reaches the surface is called lava.
magma chamber	An underground reservoir in the Earth's crust filled with magma, from which volcanic materials are derived.
magmatic fluids	Volcanic gases, especially water and carbon dioxide, dissolved in magma.
matrix	In a rock in which certain grains are much larger than the others, the containing material comprises the matrix.
microearthquake	An earthquake which is not felt but is detectable by a seismograph.
mudflow	A flow of heterogeneous earth or soil debris lubricated with a large amount of water usually following a former stream course.
neck	A vertical, pipelike intrusion that represents a former volcanic vent or throat of a volcano.
nuée ardente	A fast-moving, dense "glowing cloud" of hot volcanic ash and gas erupted from a volcano. An ash or pyroclastic flow.
open-vent phase	That part of a volcano's cycle of activity characterized by lava effusions and minor explosive activity. It may be initiated by a cataclysmic explosive eruption.
overpressure	Magma pressure in excess of lithostatic pressure, e.g., from tectonic stress. The lithostatic pressure is calculated as a fluid pressure based on the weight of overlying material
P-wave	Seismic waves in which displacements are in the direction of wave propagation.
paleomagnetism	Study of faint magnetic properties of rocks preserved from an earlier time. For example, magnetic particles were oriented with respect to the earth's magnetic field as it existed at that time and place, and were fixed by solidification of a lava.

partial crystallization	The stage of cooling of magma when it is partly solid crystals and partly liquid melt or "glass."
petrology	Study of the origin of rocks, their chemistry, mineralogy, and formation.
phenocryst	A crystal notably larger than the fine-grained or glassy matrix enclosing it.
phreatic eruption	Steam blast eruptions due to the heating of confined ground water by volcanic heat.
phreatomagmatic explosion	A volcanic explosion that extrudes both magmatic material and steam. The climatic eruption of Mount St. Helens on May 18, 1980 is believed to have started as a phreatic-magmatic eruption.
phyric	Porphyritic, containing crystals in a fine grained or glassy matrix.
plate tectonics	The theory that the Earth's crust is broken into about 10 large plates which slowly move about the surface.
Plinian-eruption	An energetic explosive eruption in which large volumes of tephra are ejected at high velocity in a tall eruption column.
pluton	A large mass of igneous rock formed at depth in the crust by solidified magma.
porphyritic	The texture of an igneous rock in which larger crystals are set in a fine-grained ground-mass, which may be crystalline or glassy or both.
potassium argon	The radiometric age dating technique. The determination of the time that has elapsed since crystallization of a rock or mineral by study of the ratio of daughter products and their parent elements.
probabalistic prediction	A very general prediction of volcanic activity in terms of years or decades, based upon studies of a volcano's history as a basis for future behavior. In contrast to some specific deterministic prediction.
pumice	A form of volcanic glass so filled with gas bubble holes that it resembles sponge and is very light. Solidified lava froth.
pyroclastic flow	A highly mobile flow of ash and other pyrodestic fragments dispursed in hot turbulent gas. The term includes or is synonymous with ash flow, nuee ardent, and glowing avalanche.
pyroclastic rock	Solid fragments formed by explosion or spraying from a volcanic vent; includes volcanic ash, dust, cinders, and blocks.

pyroxene andesite	Andesite with high pyroxene (a black, mafic mineral) content.
quartz	An important rock-forming mineral composed of silicon and oxygen (SiO_2).
Radiometric dating	Calculation of an age in years of geologic materials by any one of several age determination methods based on nuclear decay of natural radioactive elements contained in the material.
radon	A gaseous radioactive element formed by the natural radioactive decay of radium. Currently of interest in earthquake prediction.
resurgent dome	An upwarped portion of a caldera floor formed by resurgent magma pressure following a cataclysmic eruption.
rhyolite	A silicic fine-grained volcanic rock with the same composition as granite. Rhyolite lavas are typically viscous and likely to produce explosive eruptions.
s-waves	Transverse waves that travel through an elastic medium. They are commonly recorded after the p-wave, by seismographs.
seismic wave	A general term for a vibrational wave produced by an earthquake.
seismic-velocity	The rate of propagation of an elastic wave, usually measured in km/sec. The wave velocity depends upon the type of wave and the elastic properties of the rock through which it travels.
seismograph	An instrument that records the motions of earthquake waves.
seismology	The study of earthquakes, seismic waves, and the structure of the interior of the Earth.
shield volcano	A volcano in the shape of a flattened dome, built by gently sloping flows of formerly very fluid basaltic lava.
silica	A chemical combination of silicon and oxygen (SiO_2).
silicic	Rocks of relatively high silica content; rhyolite and dacite among volcanic rocks.
silicate mineral	A mineral largely composed of silcon and oxygen in various crystalline and compositional forms.
spasmodic-tremor	Closely spaced earth tremors intermediate in nature between volcanic tremor and earthquake swarm phenomena.
strato-volcano	A steep volcanic cone built up of alternating lava flows and pyroclastic deposits.

subduction zone	The zone of convergence of two tectonic plates, one of which overrides the other.
swarm (or earthquake swarm)	A series of minor earthquakes, none of which may be identified as the main shock, occurring in a limited area and time.
tectonic	Pertaining to deformation of the earth's crust. As applied to earthquakes, it is used to describe shocks not due to volcanic action or to collapse of caverns or landslides.
teleseismic	Referring to seismic waves originating from a distant source.
tephra	A general term for all airfall pyroclastic material erupted from a volcano or other vent.
tephrochronology	A chronology based on the dating of volcanic ash layers.
thermal gradient	The rate of change of temperature with distance or depth.
thrust fault	A gently inclined fault whose upper side moves relatively upward.
tiltmeter	An instrument or installation of instruments used to measure tilting of an object or an area of the Earth. Commonly employed to predict volcanic eruptions.
tuff	A rock formed of compacted volcanic fragments generally smaller than 4 mm in diameter. Lithified volcanic ash.
vent	The opening at the Earth's surface through which volcanic materials issue forth.
vesicular	Containing abundant gas bubbles.
volcanic explosivity index	An estimate of explosive magnitude for historical volcanism based upon such factors as airwave (measured by recording barographs), height of eruptive cloud, volume of eruptive products, and distances to which objects of a particular size were thrown.
volcanic system or complex	A persistent volcanic vent area that has built through recurring volcanic action a complex mixture of volcanic landforms.
volcanic tremor	Continuous oscillating ground motion with frequencies of 0.5 to 10 Hz associated with subsurface magma movement at volcanoes harmonic tremor.
xenolith	Rock fragment that is foreign to the body of igneous rock in which it occurs; an inclusion of older rock in lava or tephra.

76977-650 2-83 2M LDA

3 1175 00675 2763

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

BOOKS REQUESTED BY ANOTHER BORROWER
ARE SUBJECT TO IMMEDIATE RECALL

NOV 22 1989

PHYS SCI LIBRARY

NOV 21

PHYS SCI LIBRARY

DEC 11

NOV 29 1989

FEB 06 1990

MAR 16 1990

MAR 10 1990 REC'D

JUN 14 1990

SEP 27 1990

LIBRARY, UNIVERSITY OF CALIFORNIA, DAVIS

Book Slip—Series 458

589R

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

BOOKS REQUESTED BY ANOTHER BORROWER
ARE SUBJECT TO IMMEDIATE RECALL

JUN 04 '97
JUN 1 1 1997 REC'D
RECEIVED
JUN 1 4 1997
Physical Sciences Library
NOV 1 0 1998
RECEIVED
OCT 2 8 1998
Physical Sciences Library
FEB 2 7 2000
RECEIVED
FEB 2 8 2000
PSL

LIBRARY, UNIVERSITY OF CALIFORNIA, DAVIS
D4613 (7/92)M

UCD LIBRARY

UNIVERSITY OF CALIFORNIA, DAVIS
3 1175 01913 4249